OPERATIONS RESEARCH PREVENTIVE MAINTENANCE MODELS: APPLICATIONS FOR THE NAVY MAINTENANCE AND MATERIAL MANAGEMENT SYSTEM

James T. McCarthy

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BY

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Bachelor of Arts

Stanford University, 1964

A Thesis Submitted to the School of Government and
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University in Partial Fulfillment of the
Requirements for the Degree of
Master of Business Administration

June, 1971

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INTRODUCTION

Statement of the Basic Question

> We must think of our whole economics in terms of a preventive pathology instead of a curative pathology. Don't oppose forces; use them. God is a verb, not a noun.[1]

Buckminster Fuller's proverbial observation in "No More Secondhand God" is one of the more recent pronouncements of a basic tenet which has been repeated often in the development of civilization. The underlying notion is the foundation for such diverse current concepts as "preventive medicine," "preventive detention," or even "preventive war." This often vague, and ill defined, belief appears to generally state that there exist circumstances under which short-run sacrifice can contribute to long-run benefit. Older statements of this philosophy are many and include: "An ounce of prevention is worth a pound of cure," or "A stitch in time saves nine."[2] In American literature, Benjamin Franklin's legacy of maxims has given us:[3] "Want of care does us more damage than want of knowledge," and

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[1]Richard Buckminster Fuller, "No More Secondhand God," quoted in John Bartlett, Familiar Quotations (14th ed.; Boston: Little, Brown and Company, 1968), p. 1034.

[2]Anonymous proverbs.

[3]Benjamin Franklin, The Way to Wealth, in The Annals of America, Vol. 2 (Chicago: Encyclopaedia Britannica, Inc., 1968), p. 32.

> A little neglect may breed great mischief; for want of a nail the shoe was lost, and for want of a shoe the horse was lost, and for want of a horse the rider was lost, being overtaken and slain by the enemy; all for the want of a little care about a horseshoe nail.

This last quotation, which Franklin apparently borrowed from the earlier work of George Herbert,[4] suggests military aspects of the preventive philosophy. Historians have similarly noted a correlation between military or naval success and attention to preventive measures adopted long before the battle. Observations have included references to the preventive care and attention given to military material in anticipation of future benefit.

Mahan's assessment of the naval confrontations between the British and French fleets in the seventeenth and eighteenth centuries includes frequent reference to superior Brttish attention to such preventive measures. As Mahan notes, British commanders were often able to avoid or delay engagement with French units because their ships' bottoms were periodically "coppered" or sheathed to protect against worming deterioration. They were thus able to out-distance French ships that, although newer and often of superior designed speed, had not been protected against the material degradation of long months at sea.[5]

The practice of "coppering" is no longer a significant preventive measure among major navies. Steel, mechanically propelled

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[4] George Herbert, Jacula Prudentum, quoted in John Bartlett, Familiar Quotations (14th ed.; Boston: Little, Brown and Company, 1968), pp. 324-25.

[5] Alfred Thayer Mahan, The Influence of Sea Power upon History 1660-1783 (New York: Hill and Wang, 1957), pp. 371-451.

warships have replaced the wooden sailing ships in the last hundred years. The desirability of improving the future performance of naval material through the application of preventive policies and techniques has, however, persisted and widened in scope.

The United States Navy has given increasing attention to the identification of material problems which can be minimized through the application of maintenance policies designed to monitor, inspect, and service shipboard equipment before failures occur. Its efforts toward this end have been directed in two major areas: first, the proper design, procurement, and installation of equipment which considers the total maintenance function (preventive and corrective) which will be required; and second, the establishment of a standardized maintenance and material management system for operational ships. This latter effort has resulted in the Navy Shipboard Maintenance and Material Management (3-M) System.

Ackoff and Sasieni have defined the nature of Operations Research to be: "The application of scientific method by inter-disciplinary teams to problems involving the control of organized (man-machine) systems so as to provide solutions which best serve the purposes of the organizations as a whole." Among the basic "prototype" problems which these authors have described as most frequently recurring in Operations Research is that of Replacement. They further sub-classify the area of Replacement as including those problems involving "the selection of a preventive maintenance scheme, which is designed to reduce the probability of failure."[6]

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[6]Russell L. Ackoff and Maurice W. Sasieni, Fundamentals of Operations Research (New York: John Wiley & Sons, Inc., 1968), pp. 6-15.

There exists today a considerable body of literature in the area of preventive maintenance theory developed by Operations Research (or Management Science). These theories generally involve the modeling of a policy of preventive maintenance to determine the optimum decision for meeting objective criteria.

The purpose of this present research is to determine the degree of usefulness of existing preventive maintenance models to aid in the design and operation of the Navy shipboard 3-M System. The analysis will require a survey of both the theoretical literature and the 3-M system objectives and procedures.

Scope of the Research

This research will investigate only the shipboard 3-M system; it will not study related systems in aviation, nuclear propulsion, or special weapons activities of the Navy. Further, it is intended to limit the investigation of system objectives and procedures to those directed from the Department of the Navy level. No attempt to study the policies and practices of subordinate commands in the operating forces is to be made. The source of the bulk of 3-M information will be obtained from personnel and publications of the Office of the Chief of Naval Operations (OPNAV). Finally, in an effort to limit the scope of inquiry to a relatively narrow portion of the data available, the investigation of technical direction and procedures will be conducted only for that equipment managed by the Naval Ship Systems Command (NavShips). NavShips is but one of many technical Systems Commands which are coordinated by the Chief of Naval Material for managerial control including coordination and standardization of 3-M operation.

Desired Value to be Obtained from the Study

The application of techniques of Operations Research in the Department of Defense has been the subject of considerable investigation and literature over the past two decades. In the more limited spectrum of professional literature on naval shipboard operation and management, the 3-M System has also received much attention. 3-M has been evaluated as an application of industrial engineering, management engineering, and management informations systems. This author believes that there may be beneficial congruence between certain theories of Operations Research problem-solving and the problem-solving apparatus of the 3-M System. It is hoped that an investigation of each will reveal such similarities, dissimilarities, current connection, and potential inter-relationships as may exist. Preliminary research suggested the possibility of correlation between the two topics which this paper will attempt to document and analyze.

Research Methodology

Data has been obtained for this paper through the use of library research and direct interviews. Reference material has been obtained from public, educational, and military libraries in the metropolitan Washington, D.C. area. Particularly valuable assistance has been obtained at the U.S. Army Pentagon Library. Interviews have been conducted at the Office of the Chief of Naval Operations, the Naval Ship Systems Command Headquarters, and the Naval Ship Engineering Center.

Terminology

An attempt has been made to permit this paper to be understandable to a reader who has neither a background in the field of Operations Research nor a knowledge of the operation of the shipboard 3-M System. Nonetheless, some compromise had to be achieved to avoid the necessity of identifying and defining every technical or institutional term necessary to the research presentation. In the case of military terminology, reference has been made to the Joint Chiefs of Staff Dictionary of U.S. Military Terms for Joint Usage. Acronyms are utilized in this paper but only after their parenthetical introduction following a full title, name, or concept to which they apply.

Organization of the Thesis

Chapter II introduces the notion of preventive maintenance, describes the evolution of Operations Research interest and inquiry into this field, and selectively describes significant theories, policies, and models developed. It also provides a general overview of the nature of equipment failure and the statistical techniques and probabilistic distributions used to describe such behavior. Chapter III provides background information on the original development of the shipboard 3-M System. It then briefly describes the major elements of the System, defining the objectives and basic procedures of each. Lastly it investigates the extent of system integration in the 3-M approach and hypothesizes a possible application of quantitative techniques of Operations Research to improve the degree of integration. Chapter IV attempts to reconcile the research presented on the

theoretical aspects of preventive maintenance with that observed for the actual maintenance system. It introduces the problem of objective criteria and discusses the concept of material readiness. Finally, it offers specific recommendations on the application of Operations Research models to the existing 3-M System and recommendations on how increased model utilization could be obtained with system refinement. Chapter V briefly summarizes the major conclusions which the author has drawn from the research process. It concludes the thesis with a few general proposals for further investigation.

CHAPTER II

PREVENTIVE MAINTENANCE THEORY

Background

In a traditional discourse on preventive maintenace which encompasses no quantitative techniques, Carl Wyder has defined any "PM program" to consist of two basic activities:

1. Periodic inspection of plant assets and equipment to uncover conditions leading to production breakdowns or harmful depreciation.
2. Upkeep of plant to sterilize such conditions, or to adjust or repair such conditions while they are still in a minor stage.[1]

The explicit objectives of this industrial definition appear to focus on two distinct criteria which will remain important throughout the discussion of this paper:

1. Preventive maintenance can attempt to minimize the probability that the normal operation of an activity or enterprise is interrupted. In other words it is intended to minimize "downtime"; maximize "uptime." Or, in military terminology, the objective may be stated to maximize readiness (which might loosely be thought of as the "normal operation" of a military activity).

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[1]Carl G. Wyder, "Preventive Maintenance," in Maintenance Engineering Handbook, ed. by L. C. Morrow (New York: McGraw-Hill Book Company, 1957), p. 1-92.

2. Preventive maintenance can, alternatively, attempt to minimize the expected costs per period of an operation. If this latter criteria is adopted, it is then necessary that the nature of such "costs" be clearly specified.

The principal difference highlighted by the above distinction is that of emphasis on either the inputs or the outputs of an activity. Newer managerial control techniques might suggest a synthesis of these alternative criteria into a single measure of efficiency or effectiveness which would examine both inputs and outputs. Such a measure might involve cost-benefit or cost-effectiveness analysis and will be developed later.

The history of Operations Research inquiry into the area of preventive maintenance can be traced back approximately twenty years. Early dissertations, however, for the most part involved the determination of optimum means of "planned replacement." This is not surprising, since an attempt to classify preventive maintenance theory within the broad major investigative areas of Operations Research would probably classify it as a subsidiary element of general Replacement Theory. Further, a more comprehensive view of this entire field would better describe the total investigative discipline as that of Renewal Theory (whether the renewal consists of replacement or repair--maintenance).

In 1941, Mr. N. R. Campbell of the General Electric Company of England utilized a complicated set of integral equations to determine the most economic policy involving the mass replacement

of lightbulbs. His techniques probably represent the first application of the methodology of the emerging discipline of Operations Research in the area of preventive maintenance. The military activities of the following years produced a rapid expansion of this type of research with considerable emphasis in the United States on the study of equipment reliability theory--an area closely allied to the subject of renewal.[2]

In 1949, George Terborgh made a significant contribution to the general field of Renewal Theory with his pioneering work, Dynamic Equipment Policy. Terborgh's examination of the nature of "Primary" and "Secondary" Replacement, the functional degradation of equipment, and his two basic concepts--Operating Inferiority and the Adverse Minimum--all greatly expanded the scope of investigations into industrial equipment replacement. He was, however, primarily concerned with replacement policy as it affects the capital budgeting decisions of the manager. He did not stress the nature of failure in service or its costs, and his analytical techniques are not readily adaptable for maintenance application. His discussion of the gradual change of state generally described as obsolescence and the opportunity costs inherent in a full treatment of replacement questions have provided later researchers in preventive maintenance with a significant base of theory.[3]

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[2]M. Kammins and J. J. McCall, Rules for Planned Replacement of Aircraft and Missile Parts, Rand Memorandum 2810-PR (Santa Monica, California: The Rand Corporation, 1961), p. iii.

[3]George Terborgh, Dynamic Equipment Policy (New York: McGraw-Hill Book Company, 1949), pp. 1-91.

The first explicitly definable investigation of general preventive maintenance/replacement by members of the emerging Operations Research discipline can probably be located at the Rand Corporation in early contract work for the Air Force. In 1952, A. A. Alchian prepared a report, Economic Replacement Policy, which demonstrated the first deterministic solution to the cost minimization problem involved in the replacement of deteriorating equipment.[4] This early endeavor provided a solid foundation upon which a continuing pursuit of improved techniques and means of application have been developed by others. The extension of early replacement theory into more general renewal theory initiated some research into the problems of optimum maintenance policies for equipment--particularly where that equipment is known, or thought, to exhibit stochastic failure characteristics.

Other centers of research contributed to the present body of literature in the preventive maintenance area. The commercial airlines were quick to appreciate the applicability of the mathematical procedures developed at the Rand Corporation and made early use of mathematically derived maintenance programs constrained, of course, by the high degree of governmental regulation on maintenance standards for aircraft. Still other researchers, particularly Barlow, Hunter, and Proschan at Sylvania, developed mathematical theories to define and quantify reliability. Newer mathematical tools, particularly the technique of dynamic programming, provided

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[4] John J. McCall, "Maintenance Policies for Stochastically Failing Equipment: A Survey," Management Science, Vol. 11, No. 5 (March, 1965), pp. 493-502.

new avenues of effective application of preventive maintenance concepts.[5] Throughout this developmental period, 1952-1962, the increasing accessibility and capabilities of electronic computers were providing a realistic means of demonstrating the working application of the mathematical models that had been constructed.

Among the most prolific writers in recent years has been John J. McCall. McCall is a Professor of Management Science at the University of Chicago and was formerly a research economist for the Rand Corporation. Much of McCall's published work at the Rand Corporation (1959-1966) concerned the development of procedural rules for the planned replacement of military weapons systems, descriptions of "opportunistic" replacement ind inspection policies, and associated support and supply systems. In more reeent years, he has made an additional contribution through articles which have surveyed the field to categorize the various maintenance policies which he and other researchers have developed. In a 1965 article in Management Science, he describes the general classification of maintenance policies for stochastically failing equipment. This classification can be briefly outlined as:[6]

I. Maintenance Policies for Known Distributions of Times to Failure

    A. Preventive Maintenance Policies

        1. Periodic Preventive Maintenance Policies

        2. Sequential Preventive Maintenance Policies

        3. Preventive Maintenance Policies for Equipment with Several Parts

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[5] Kammins and McCall, Rules for Planned Replacement, pp. 1-3.

[6] McCall, "Maintenance Policies: A Survey," pp. 493-512.

B. Preparedness Maintenance Policies

1. Periodic Preparedness Policies

2. Sequential Preparedness Policies

3. Preparedness Policies for Equipment with Several Parts

4. Multi-state Preparedness Policies

II. Maintenance Policies for Unknown Distributions of Times to Failure

A. Minimax Maintenance Policies

1. Preventive Maintenance Policies

2. Preparedness Policies

B. Policies Selected by Bounding Techniques

1. Preventive Maintenance Policies

2. Preparedness Policies

C. Adaptive Maintenance (Preparedness) Policies

In a later discussion (1967) in the book, Defense Management, McCall more briefly describes the above classification as an incomplete summary of the research in stochastic maintenance policies. He notes that two other broad areas of investigation can be similarly categorized and discussed--Deterministic Maintenance Policies and investigation into the relationship between Maintainability and Reliability.[7] It is not within the scope of this present work to investigate these latter two areas. Indeed, we cannot even attempt to fully survey the research limited to stochastic maintenance policies but must concentrate on a limited number of specific models.

Before leaving this brief survey of research and investigation into maintenance theory, it may be valuable to note that much of the literature must be located through inquiry into adjacent fields of

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[7] John J. McCall, "Maintenance," in Defense Management, ed. by Stephen Enke (Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1967), pp. 166-169.

Operations Research. Maintenance models have been explored by research in such fields as queueing theory, computer simulation, and inventory theory. Indeed, the interdependent relationship between inventory and replacement models has been an area of special attention for separate study. Thus, while we stated earlier that Preventive Maintenance Theory can generally be thought of as a subsidiary area to Replacement (Renewal) Theory, it may now be apparent that no neat general categorization is available. Fortunately, the bulk of our subsequent theoretical investigation can be directed to a few general stochastic models which, on the basis of their stated assumptions, appear to offer potential applicability to the Navy's Maintenance and Material Management (3-M) System.

Periodic Cost Minimization Model

The basic preventive maintenance model which has received the most extensive attention is the periodic model to minimize total maintenance costs per unit time. It rests upon two basic assumptions (or qualifications) for a piece of equipment:

a. The equipment should exhibit a strictly increasing tendency to fail with age.

b. The after-failure cost of maintenance (corrective) is greater than the before-failure cost of maintenance (preventive).

The first qualification allows us to begin the model by describing a continuous probability density function for failure of the

equipment as $y = f(t)$. The second qualification allows us to define the before-failure costs (per maintenance action) as B, the after-failure costs as A, and to require that $A > B$.

Given this base of data, it is then possible to compute the useful values which will allow determination of an optimal preventive maintenance policy. These include, but are not limited to:

u = average life before failure without preventive maintenance

x = average life before failure with preventive maintenance

C = expected maintenance costs per unit time period when preventive maintenance period T is expressed in the given unit time.

T = preventive maintenance period such that $\frac{1}{T}$ = periodicity

$p = F(t)$; cumulative probability of failure

$q = [1-F(t)] = 1-p$; cumulative probability of survival.

Using this nomenclature it can then be shown that:

(1) Average Life Before Failure Without P.M.

$$u = \int_0^\infty tf(t)dt \quad ,$$

(2) Average Life Before Failure With P.M.

$$x = \int_0^T tf(t)dt + T\int_T^\infty f(t)dt \ .$$

From (1) and (2), it can further be demonstrated that the Costs per unit time for a P.M. program at time T is expressed as

$$(3) \qquad C = \left[A \int_0^T f(t)dt + B \int_T^\infty f(t)dt \right] \frac{1}{x} .$$

Further, $p = \int_0^T f(t)dt$, and $q = 1-p = \int_T^\infty f(t)dt$. Substitution into (3) yields:

$$(4) \qquad C = \frac{(A-B)p + B}{x} .$$

Finally, by taking $\frac{dC}{dT}$ and setting it equal to zero, we can determine a minimum value for C (the second derivative can be shown to be positive). This minimum is achieved when:

$$(5) \qquad \frac{f(T)}{q} = \int_0^T tf(t)dt + Tf(T) - p = \frac{B}{A-B} .$$

For simpler solution by iteration when the possible values of T are constrained to weeks, months, years, etc. (as in the Navy's 3-M system), we can utilize P_t in place of $f(t)$ where P_t is the cumulative probability of failure to time t less the cumulative probability of failure to time $t-1$. Or $P_t = F(t) - F(t-1) = p_t - p_{t-1}$ and the minimum cost can be determined by evaluating:

$$(6) \qquad \frac{P_T}{q} \sum_{t=1}^{T} tP_t + TP_T - p = \frac{B}{A-B} .$$

The above equation, as shown by Richmond, lends itself easily to tabular solution and is certainly easily adaptable to computer

solution involving a very simple program.[8]

Although equations (5) and (6) appear clear, they are sometimes modified and appear as:[9]

$$\text{(7)} \qquad j(T)\int_0^T (1-p_t)dt - p_T = \frac{B}{A-B}$$

where

$$\begin{aligned} j(t) &= \frac{d}{dt}\,[\log(1-p_t)] \\ &= \frac{d}{dt}\,\{\log[1-F(t)]\} \\ &= \frac{f(t)}{[1-F(t)]} \\ &= \frac{f(t)}{q} \end{aligned}$$

or

$$j(T) = \frac{f(T)}{q} \quad ,$$

illustrating the equivalence of the equations.

Equation (7) introduced the value $j(t)$ which can be defined as the conditional probability of failure for the interval t to $t+1$ given that the item has survived to time t. As shown above, it is equal to the prior probability that an item will fail in the interval t to $t+1$, $f(t)$, divided by the complement of the prior cumulative probability that the item will have failed by time t, $[1-F(t)]$, which can also be described as the cumulative probability of survival to time t.

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[8] Samuel B. Richmond, Operations Research for Management Decisions (New York: The Ronald Press Company, 1968), pp. 251-257.

[9] McCall, "Maintenance," in Defense Management, p. 172.

Preparedness Models

Barlow and Hunter have done research into optimum preventive maintenance policies which may be best described as "preparedness" models. They have described their conclusions regarding two distinct possible policies as:[10]

> one which is useful in maintaining simple equipment and another which is useful in maintaining large, complex systems. For less complex equipment, repair at time of failure (or replacement) may actually correspond to general overhaul. . . . However, for more complex systems such as computers, preventive maintenance is commonly scheduled after a certain number of operating hours have accumulated. Between maintenance periods, failures are repaired as quickly as possible.

They define an optimal policy as that which will maximize their "limiting efficiency"--the fractional amount of up-time over long intervals. This criterion can be formally defined as an efficienty (EFF) such that:

1. EFF_T = expected fractional amount of time system is on during $[0,T]$
2. $EFF_\infty = \lim_{T\to\infty} EFF_T$ --the "limiting efficiency" used for policy evaluation.

The two policies which are then evaluated utilizing this criterion can be described as:

Policy I

Perform preventive maintenance after t_o hours of continuing operation without failure. t_o is allowed to be infinite; if system failure occurs prior to t_o, emergency maintenance is performed at

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[10]Richard Barlow and Larry Hunter, "Optimum Preventive Maintenance Policies," The Journal of the Operations Research Society of America, Vol. 8, No. 1 (January-February, 1960), p. 90.

time of failure and preventive maintenance is rescheduled. The assumption is made that the system is as good as new after either emergency or scheduled maintenance (or replacement) is performed.

Policy II

Perform preventive maintenance on the system after it has been operating a total of t^* hours regardless of the number of intervening failures. t^* is allowed to be infinite. If the system fails before t^*, only interim, minimum maintenance is performed. The assumption is made that the system is as good as new after scheduled preventive maintenance and that the system failure rate is not disturbed by performing minimim repairs.

Using much of the nomenclature developed for the periodic cost minimization model, we recall that for a failure distribution $F(t)$, with density (first derivative) $f(t)$, the proneness of system failure at time t can be expressed as:

$$j(t) = \frac{f(t)}{[1-F(t)]} ,$$

and that for cases where $j(t)$ is an increasing function of t, preventive maintenance appears plausible. As before, u = expected time to failure without preventive maintenance. For our new models, we add the quantities:

t_o = Type I Preventive Maintenance Period

t^* = Type II Preventive Maintenance Period

T_s = Expected time to perform scheduled maintenance (equivalent to the B or Before situation in the cost minimization model). Policy I or II

T_e = Expected time to perform emergency maintenance (equivalent to the A or After situation in the cost minimization model). Policy I

T_m = Expected time to perform minimum maintenance. Policy II.

As reported by Barlow and Hunter, an optimum Type I policy is given by the value for t_o which satisfies the familiar equation:

$$j(t_o) \int_0^{t_o} [1-F(t)]dt - F(t_o) = \frac{T_s}{T_e - T_s} \quad \text{when} \quad T_e > T_s$$

with a limiting efficiency:

$$EFF_\infty = \frac{1}{1 + (T_e - T_s) j(t_o)} \ .$$

When $T_e \leqslant T_s$, the optimum policy is no preventive maintenance, i.e., $t_o = \infty$ with a limiting efficiency:

$$EFF_\infty = \frac{u}{u + T_e} \ .$$

In a similar fashion, they illustrate a proof using general renewal theory that an optimum Type II policy is given by a value for t^* which satisfies the equation

$$\int_0^{t^*} t\ j(t)dt = \frac{T_s}{T_m}$$

with a limiting efficiency expressed as:

$$EFF_{\infty} = \frac{1}{[1 + T_m \; j(t^*)]} \; .$$

For any given time to perform scheduled maintenance (T_s), the selection between Types I and II policies involves an examination of the corresponding values of emergency and minimum maintenance actions (T_e and T_m) for the system. We can graphically display an example indicating the selection boundary between the two policies where their limiting efficiencies are equal:

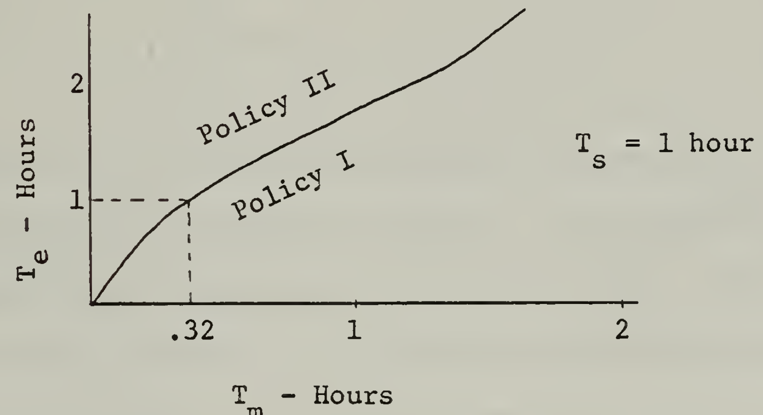

Fig. 1.--Selection Boundary for Preparedness Policies

It should be clear that the shape of the boundary curve is determined by the formulae developed for the "limiting efficiencies" and is dependent upon the characteristics of the failure distribution. Thus far, we have not considered the many possible distributions which might adequately display actual failure characteristics. A considerable amount of the basic literature on preventive maintenance has devoted itself to this implicit question and we can summarize several major findings to indicate the importance of this investigation.

Types of Distributions

The cumulative density function (CDF) of failure, $F(t)$, for any system must increase with time and $F(\infty) = 1$. The derivative of this function, as noted earlier, is the probability density function (PDF) of failure, $f(t)$, and can decrease, remain constant, or increase with time subject to the restriction: $f(t) \geqslant 0$ such that

$$F(t) = \int_0^t f(x)\,dx$$

and

$$\int_0^\infty f(x)\,dx = 1 .$$

The applicability of preventive maintenance action hinges on the inter-relationship of the CDF and PDF for a given system as expressed by the conditional failure rate (FR) for the system $j(t)$ which has been previously defined. It is this distribution which must be examined in the analysis of preventive maintenance theory.

The most significant distributions which have been found adequate to describe particular system failure characteristics are the exponential, normal, log-normal, gamma, and Weibull. The CDF, $F(x)$; PDF, $f(x)$; and FR, $j(x)$ for each can now be examined and the implication for preventive maintenance action briefly noted.

Exponential Distribution

CDF: $F(x) = 1 - e^{-\frac{x}{\mu}}$

PDF: $f(x) = \frac{1}{\mu} e^{-\frac{x}{\mu}}$ $\qquad \mu$ = mean life

FR: $j(x) = \frac{1}{\mu}$ (constant)

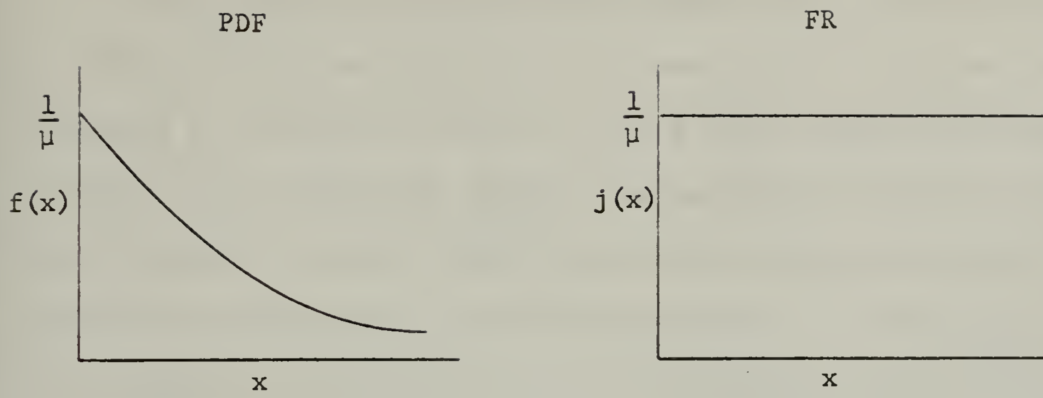

Fig. 2.--The Exponential Distribution

The exponential distribution[11] is the distribution without a memory. It exhibits a constant conditional probability of failure which is not a function of the independent variable.

Preventive maintenance (or replacement) cannot be justified for a system known to fail exponentially. The newest piece of equipment, or newest system, will have the same likelihood of failure as the oldest. In the cost minimization model, money will be poorly spent if a PM program is adopted. Similarly for maximization of operating time, PM is not the answer. Redundancy, rather than preventive maintenance, must be used to improve system reliability.

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[11]The Poisson distribution, a discrete probability distribution defined by $P(x) = \frac{e^{-m}m^x}{x!}$ is not identical to the Exponential distribution, a continuous probability distribution--but both are frequently used in queueing theory and the literature is frequently in error by equating them.

It has been hypothesized that systems tend to fail exponentially when they are characterized either by human errors, or by well-developed techniques for minimizing failure, or by a wide range of environmental severity.[12] For mechanical systems, the exponential distribution is characteristic of complex, multi-part installations where such a random failure distribution may actually reflect the "averaging" effect of the summation of sub-system failure distributions which are not exponential in nature.

Normal (or Gaussian) Distribution--truncated at zero

μ = mean of the distribution

σ = standard deviation of the distribution

Since $\int_0^\infty f(x)dx = 1$, b must be such that:

$$\frac{1}{b} = \frac{1}{\sigma}\int_0^\infty \phi\left[\frac{x-\mu}{\sigma}\right]dx$$

$$= \frac{1}{\sigma}\int_0^\infty \phi(z)dx$$

where

z = standard normal variable with

$\mu = 0$

$\sigma = 1$ i.e. $z = \frac{x-\mu}{\sigma}$.

$$\text{CDF:}\quad F(x) = \frac{b}{2\pi}\int_{-\frac{\mu}{\sigma}}^{z} e^{-\frac{z^2}{2}}dx = b\Phi(z)$$

[12] D. J. Davis, "An Analysis of Some Failure Data," Journal of the American Statistical Association (June, 1952), pp. 115-150.

$$\text{PDF:} \quad f(x) = \frac{b}{\sigma\sqrt{2\pi}}\, e^{-\frac{z^2}{2}}$$

$$= b\phi(z)$$

$$\text{FR:} \quad j(x) = \frac{\phi(z)}{1-\Phi(z)} = j(z)$$

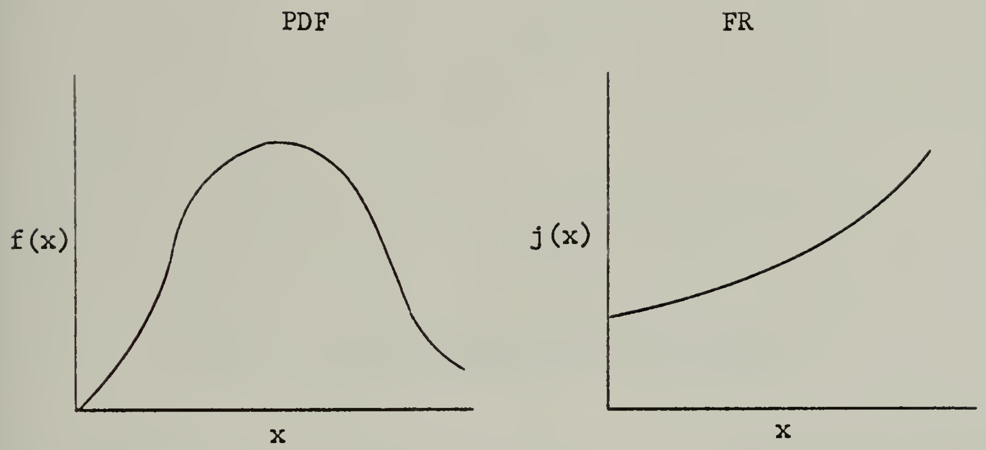

Fig. 3.--The Normal Distribution

One analysis found the following types of equipment exhibiting failure characteristics corresponding to a normal probability distribution: incandescent light bulbs; dry cell batteries; and electric bus motors (for their time to initial failure).[13] A sister distribution to the normal is the log-normal where μ is replaced by x = geometric mean (the anti-logarithm of the mean of the logarithms), and σ is replaced by g = geometric dispersion (the antilogarithm of the standard deviation of the logarithms, i.e. $\ln g = \sigma$). Unlike the normal distribution,

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[13] <u>Ibid</u>.

the FR for a log-normal distribution need not be strictly increasing but takes the form:

Log-Normal Distribution

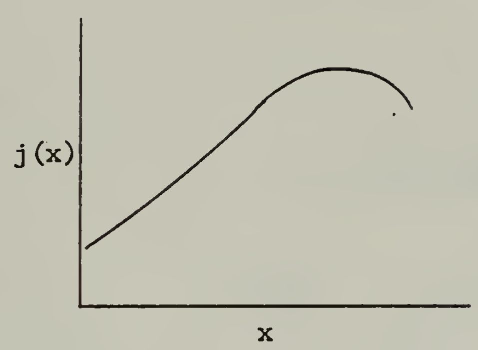

Fig. 4.--The Log-Normal Distribution

The log-normal distribution illustrates the first of several distributions where preventive maintenance can sometimes, but not always, be justified.

Gamma Distribution

a = shape parameter

b = scale parameter

$0 < x < \infty$

CDF: (For a a positive integer)

$$F(x) = 1 - e^{-bx} \sum_{i=0}^{a-1} \left[\frac{(bx)^i}{(i)!} \right]$$

$$\text{PDF:} \quad f(x) = \frac{b^a}{(a-1)!} x^{a-1} e^{-bx}$$

$$\text{FR:} \quad j(x) = \frac{b^a x^{a-1}}{(a-1)! \sum_{i=0}^{a-1} \left[\frac{(bx)^i}{(i)!}\right]}$$

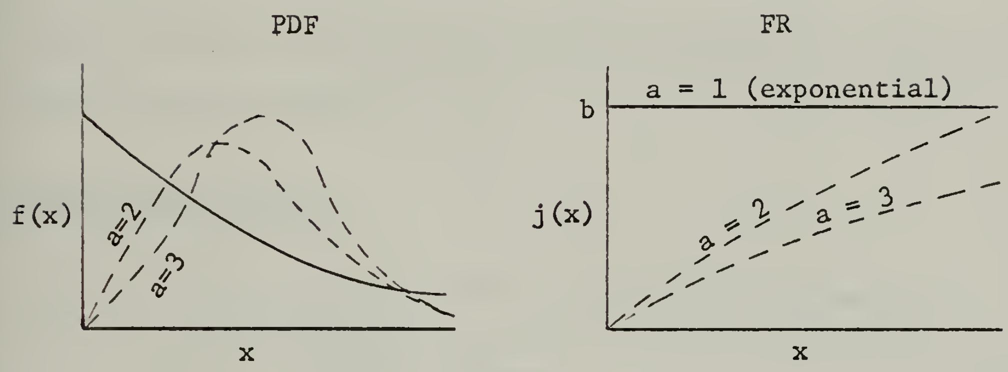

Fig. 5.--The Gamma Distribution

The gamma distribution has been widely used in management science models. This distribution is closely related to the exponential function (the exponential is the special case of the gamma where parameter $a = 1$). Further, it can be called the "natural conjugate"[14] of the Poisson distribution. This can be shown clearly by re-writing the CDF formula as:

$$F(m) = 1 - \sum_{x=0}^{a} \frac{m^x e^{-m}}{x!}$$

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[14] W. L. Shapleigh, "Reliability Testing," quoted in <u>The Concept of Material Readiness as Applied to Naval Vessels</u> by Capt. J. L. McVoy (Washington, D.C.: Office of the Chief of Naval Operations (Op 433F-1), 1970), p. 114.

where the value to the right of the summation sign is the expression for a Poisson probability distribution.[15] Finally, in the special case of the gamma where $2a$ = positive integer, the gamma distribution is known as the Chi-Square Distribution so widely used in statistical testing procedures. Obviously, from examination, it is apparent that preventive maintenance for equipment with failure characterized by a gamma distribution will only be justified when $a > 1$.

Weibull Distribution

(disregarding the usual "location" parameter")

a = "scale" parameter

b = "shape" parameter

CDF: $F(x) = 1 - e^{-ax^b}$

PDF: $f(x) = bax^{b-1} e^{-ax^b}$

FR: $j(x) = bax^{b-1}$

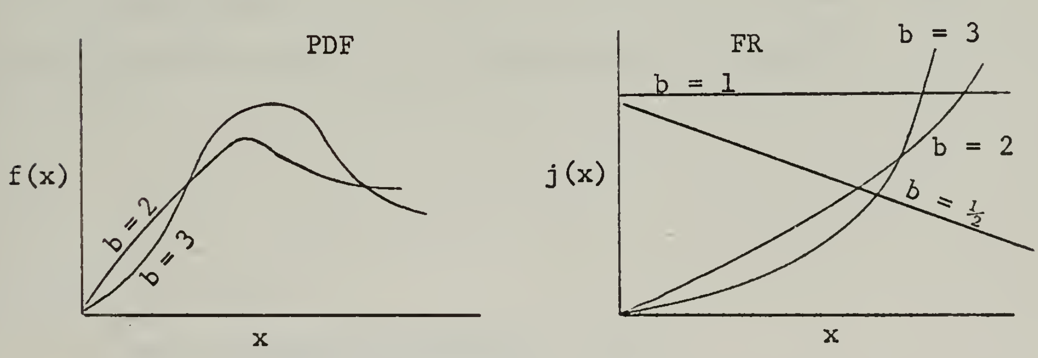

Fig. 6.--The Weibull Distribution

[15] Richmond, Operations Research, p. 218.

Preventive maintenance can only be justified for Weibull distributions with a shape parameter > 1. Weibull distributions have been useful primarily because they can realistically depict composite systems according to the values assigned to the scale, shape, and location parameters. By changing these values, this distribution can assume the identities of the exponential, normal, or mixed distributions.[16] Because of the complexity of the equations, the Weibull distribution is most often utilized where computer solution is available.

Composite Failure Distributions

The real life failure data from a piece of equipment may not correspond closely to one of the standard distributions. Over the entire life of the system, it may exhibit changing failure characteristics. Kammins and McCall have described the three principal types of "mortality characteristics" as: Burn-In, Random, and Wear-Out. This changing behavior may represent the maturation of the failure rate over the life of the equipment and is most representative for simple, mechanical systems. This composite distribution can be illustrated as below:[17]

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[16] McVoy, Material Readiness, p. 99.

[17] Kammins and McCall, Rules for Planned Replacement, p. 2.

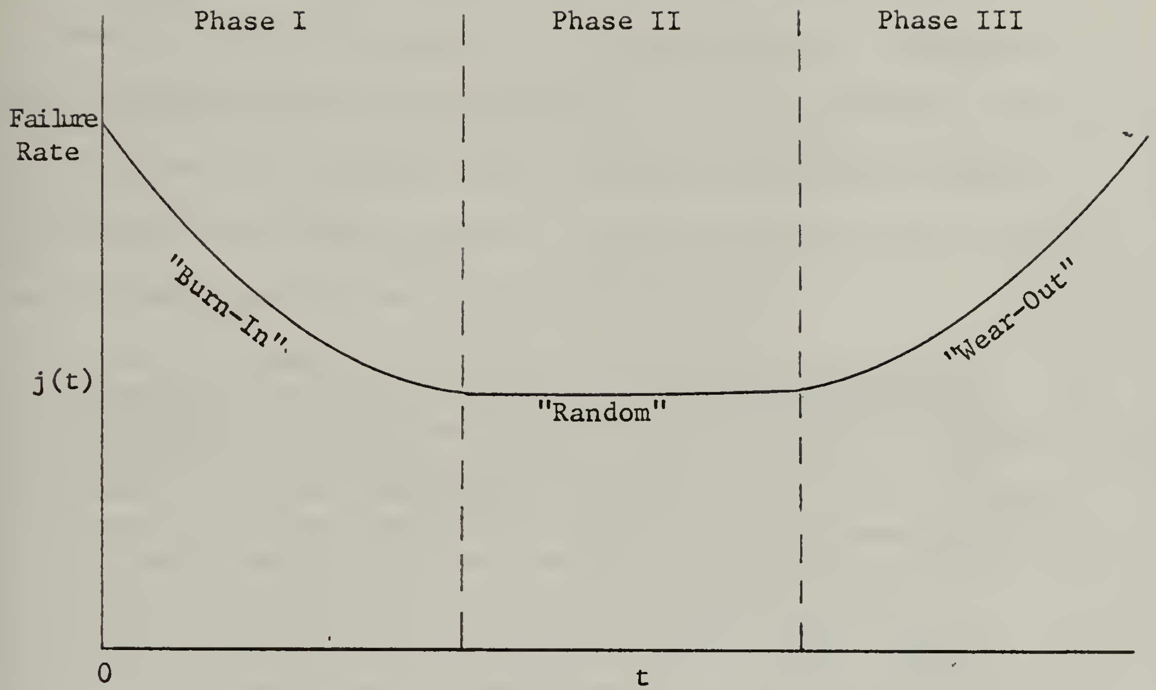

Fig. 7.--A Composite Distribution

Thus, it may be possible to represent the early phase of equipment life with decreasing failure rate by a gamma distribution with certain parameters. Later, an exponential distribution may adequately describe the failure behavior for a portion of the equipment life. Finally, the final period, Phase III, may be approximated by a normal distribution displaying the increasing rate of failure and justifying the installation of some type of preventive maintenance policy.

Group Replacement

Our discussions to this point have concerned decisions, policies, and characteristics of individual items subject to the

possible maintenance function. It may sometimes, however, be preferable to consider groups of like equipment and investigate the desirability of group replacement in lieu of individual repair or replacement at failure. Such a policy could either complement a preventive maintenance program or serve in place of one. Ackoff and Sasieni briefly discuss the possibility:[18]

> It often happens that a system contains a large number of identical low-cost items that are increasingly liable to failure with age and that there is a setup cost for replacement that is independent of the number replaced. In such cases, it may be advantageous to replace all items at fixed intervals. Such a policy is called group replacement and is particularly attractive when the value of any individual items is so small that the cost of keeping records of individual ages cannot be justified. The classic example of such a policy is that used in replacing street light bulbs; the major cost of replacement is the cost of bringing a truck and crew to the defective bulb. Once the crew is on the street, the additional labor cost of replacing every bulb is extremely small. [Italics mine.]

A simplified model for this policy can be presented. If the cost of replacement of all the items in the group (i.e. group replacement) = C_G and the cost of the individual items replaced as they fail = $C_I(t)$ where t = time since last group replacement (or installation), then the total cost, K, per group replacement cycle is

$$K = C_G + C_I(t)$$

and with a group replacement interval, T, the average cost per unit time, C_{AVG}, is

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[18] Russell L. Ackoff and Maurice W. Sasieni, Fundamentals of Operations Research (New York: John Wiley & Sons, Inc., 1968), pp. 211-213.

$$C_{AVG} = \frac{1}{T}\left[C_G + C_I(T)\right]$$

which can be seen to be composed of two divergent functions-- $\frac{C_G}{T}$ and $\frac{C_I(T)}{T}$. This allows us to illustrate the composition of the average cost function.

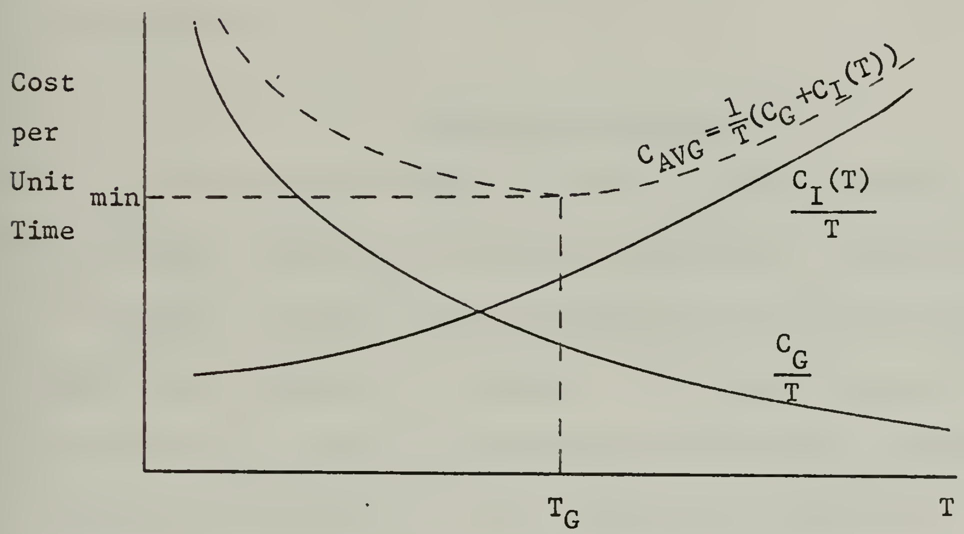

Fig. 8.--Group Replacement - Average Cost Function

Obviously, the nature of the function $C_I(T)$ will be derived from the probability density function of failure. It is possible to solve such a model analytically using Markov transition matrices and fixed point determination. A simpler, and less precise, determination of time T_G can be achieved by simply tabulating $\frac{C_G}{T}$ and $\frac{C_I(T)}{T}$ and initiating group replacement whenever their sum, C_{AVG}, is observed to have reached its first minimum. Such a policy, while resulting in a T_G greater than necessary, may be quite adequate--particularly if the curvature of C_{AVG} is relatively

flat near minimum. In any instance, as for all models discussed to date, the principal assumption must be that conditional probability of failure increases with age. This restriction is so common to preventive maintenance problems that it may be refreshing to now turn to a class of problems where it need not be adhered to.

Preventive Inspection

In the previous models, we have generally presumed that any equipment failure was detected immediately. This may be valid for equipment in more or less continuous operation where human monitoring is frequent or constant. But certain classes of equipment may only be used or operated under infrequent or emergency conditions and hence will not be consistently monitored. If such equipment deteriorates with age, it may not be available for use when needed. A compound problem is created:[19]

> The only way to make certain that it is in working order is to inspect it, but while it is being inspected, it is unavailable for use as the need arises. The problem is to find how often to inspect it so as to maximize the proportion of time during which it is in working order.

Given that the stored item is uninspected for the interval $[0,x]$, it has a probability $F(x)$ of working at age x.

a. Inspections take time t_1. We can assume for the simplest model that if any defects are present they will be found and repaired to "good as new" condition. Later, we can allow for the possibility of Type I and II statistical errors.

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[19] *Ibid.*, p. 214.

b. If defects are found, they are repaired in time t_2 .

c. The inspection interval is at time t from last inspection period (including repair time interval if any).

When inspected, the probability that the item is good is $F(t)$ and the item will again be good (after inspection only) at time $t + t_1$. The probability that the item is defective is $[1 - F(t)]$, and in this case, it will again be good at time $t + t_1 + t_2$. The average time required before the item is known to be good is:

$$(t_1 + t_2)F(t) + (t_1 + t_2 + t_3)[1 - F(t)] = t + t_1 + t_2[1 - F(t)] .$$

It can be shown that the expected amount of time during which the equipment is good will be $G_t = \sum_0^{t-1} F(x)$. Therefore, the proportion of useful time is $P(t)$ where

$$(1) \qquad P(t) = \frac{\sum_0^{t-1} F(x)}{t + t_1 + t_2 [1 - F(t)]} .$$

The optimal policy is that which maximizes $P(t)$. For an exponential failure distribution, $F(x) = j(t)^x = K^x$ where K = constant; and it can be bhown that from (1):

$$P(t) = \frac{1 + K + K^2 + \cdots + K^{t-1}}{t + t_1 + t_2 (1 - K^t)}$$

and

$$(2) \qquad \frac{1}{P(t)} = (1-K)\left(t_2 + \frac{t + t_1}{1-K^t}\right)$$

and the optimal policy will be to minimize the right side of equation (2). For non-zero, finite t, $P(t)$ is not infinite and must have a unique minimum.

CHAPTER III

THE NAVY'S 3-M SYSTEM

Background

In the preceding chapter, an examination was made of representative examples of specific preventive maintenance theories advanced in the field of Operations Research in the two decades following World War II. Before beginning a description of the shipboard preventive maintenance system as it exists today, it may be valuable to highlight the Navy's involvement in prior efforts of preventive inspection, group replacement, and preventive maintenance in the shipboard area during the same time interval.

By the post-World War II era, standardization of shipboard maintenance instructions and guidelines had begun to cluster into three broad areas:

1. Electronics

   (Radios, radars, sonars, and the like--equipment which contained electronic circuitry principally characterized by the presence of vacuum tubes - and their associated test equipment--voltmeters, signal generators, oscilloscopes, etc.)

2. Ordnance

   (Naval guns with all associated ammunition storage and handling equipment; anti-submarine ordnance

systems, torpedoes; fire control equipment including electro-mechanical computers; optical sighting, tracking, and ranging gear; small arms; etc.)

3. Hull, Mechanical and Electrical

   (The ship's structure; its mechanical equipment used for both main propulsion and auxiliary support; electrical generation, distribution, and appliance equipment; etc.)

This classification correlates both with the three operating departments of a combatant surface ship (Operations, Weapons, and Engineering), and with the evolution of senior technical commands (formerly Bureaus of the Department of the Navy and now Systems Commands of the Naval Material Command) concerned with Electronic, Ordnance and Ship Systems throughout the Navy.

In the area of shipboard hull, mechanical, and electrical maintenance, requirements were prescribed for any ship from a variety of command and directive sources, including:

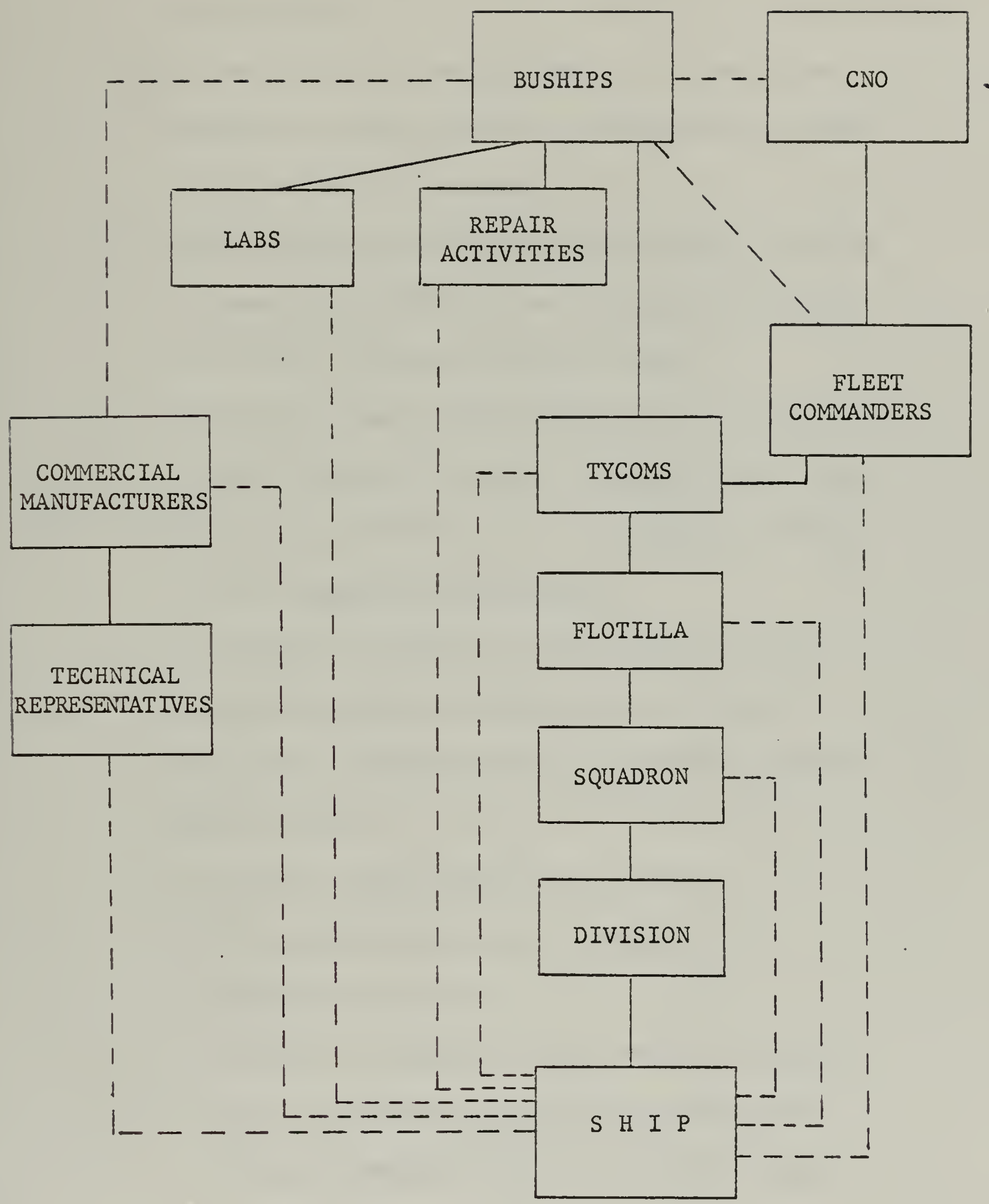
1. Requirements established by the commanding officer of the ship.
2. Requirements from senior operational commanders (Division, Squadron, Flotilla, and Fleet Commanders).
3. Requirements from fleet ship type administrative commanders (e.g. Commander, Cruiser-Destroyer Forces--Atlantic Fleet).
4. Requirements from the Department of the Navy Bureaus charged with the maintenance management of such shipboard material--the Bureau of Ships (BuShips).

Other sources of guidance or direction for the individual operating unit (either duplicating or supplementing the above breakdown) would include at least:

1. Manufacturer's recommendations as delineated in instruction and maintenance manuals.
2. Suggestions from manufacturer field technical representatives.
3. Direction or guidance from the Navy Board of Inspection and Survey.
4. Technical advice from Navy laboratories (e.g. the Navy Boiler and Turbine Laboratory at Philadelphia, Pennsylvania).
5. Recommendations of Navy repair activities--Shipyards, Repair Facilities, Industrial Managers, and Repair Ships (tenders).

All of these diverse sources for guidance were highly interrelated, but on the subject of preventive maintenance standards, there existed no final authority for coordinating and controlling their activity. The impact of this multi-channeled flow of maintenance direction and advice to an individual ship is illustrated by Fig. 9.

The most comprehensive and best documented of these impacting forces was the Engineer's "Bible"--the Bureau of Ships Technical Manual (BSTM). This 3-volume reference work contained almost 100 chapters covering practically all aspects of marine engineering within the hull, mechanical, and electrical sphere. Mastery of this massive manual was complicated by several factors:



Command Relationships ————————

Other Lines of
Maintenance Guidance — — — —

Fig. 9.--Maintenance Guidance and Direction Before 3-M

1. Its content varied from suggestive to permissive to directive.
2. It was subject to only infrequent revision and required further directive consultation to ensure the timeliness of authority.
3. Each chapter was separately indexed and there was no means to determine cross-indexing of requirements which crossed functional lines.
4. Shipboard copies of the document were generally severely limited such that a complete manual was typically available only to the Engineer Officer and his immediate subordinates.
5. Reporting requirements, where existent, were typically buried in chapter text and often duplicated coverage of other information systems. These included:
    a. Letter reports concerning specific inspections, material conditions, or failure detection.
    b. Informal Equipment Failure Reports designed to be voluntarily submitted through semi-official channels so as to stimulate open communication of failure data without the stigma of a required discrepancy report.
    c. Periodic performance reports concerning system tests and typically based on the timing of the ship's overhaul cycle.

The nature of this era of shipboard maintenance management was summarized recently by Rear Admiral W. A. Brockett, former Chief of the Bureau of Ships who expresses the need for a change in the environment from that of fragmentation to one of integration:[1]

> Not so many years ago, shipboard maintenance lessons were shared as gray-haired engineer officres of sister ships met over coffee in log rooms or ward rooms [where they discussed] . . . the expertise of care and feeding the plant endured by dint of long-hour tours of duty. [sic] The idea of profiting from hard knocks is as old as man himself, but a more fluid and demanding technology plus the mobility of our human resources demands that we systemize the vast mass of experience for organizing the bits of data so as to find the meaningful trends, share the lessons, and progress toward a higher level of effective utilization of resources and Fleet material readiness.

System Development

It is not essential to this current research to examine in detail the historical evolution of the existing 3-M system, but a few brief notes may aid in understanding its existing composition. Initial implementation as a developmental pilot program was begun in early 1963. Design, installation, and refinement of a system of standardized preventive maintenance procedures and requirements was conducted aboard the ships of Destroyer Squadrons Seven and Thirty Two. Preliminary testing of what was to become the current Planned Maintenance Sub-System had been conducted by experienced engineering maintenance personnel of the Fleet Work Study Groups on board the U.S.S. Lowry (DD-770) and the U.S.S. Agerholm (DD-826).[2]

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[1] W. A. Brockett, "Professional Notes," U.S. Naval Institute Proceedings, Vol. 95, No. 5 (May, 1969), p. 145.

[2] D. Ritchie, "Planned Maintenance--It Works," U.S. Naval Institute Proceedings, Vol. 91, No. 9 (September, 1965), p. 144.

It was recognized that standardization of procedures at the operating level for specific equipment was only a partial contribution to better maintenance results and improved readiness. An information system was required to provide managers at all echelons responsible for maintenance and material support with detailed information on maintenance action for further planning, improvement, and timely support of fleet requirements. This general problem was given under contract by the Office of Naval Research to the Logistics Research Project of the George Washington University in January, 1963.[3] This Project, which had been active in both Army and Navy logistical research since 1949, had previously provided valuable assistance to the Navy in the improvement of shipboard inventory control procedures. During 1961-62, it had worked on the problems of maintenance and material support for the Polaris Weapons System project. Much of this previous research was directly applicable to the problem of developing an integrated management information system for the 3-M concept. It is further useful to note that many of these same researchers had been active in the inquiry into the definition of a useful material readiness index for shipboard application.[4]

The Logistics Research Project worked jointly with the Logistics and Mathematical Statistics Branch of the Office of Naval Research and conducted a survey of information requirements for

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[3] Staff, Logistics Research Project, A Survey of Information Requirements for Navy Maintenance and Material Management (Washington, D.C.: The George Washington University, 1964), p. 1.

[4] James E. Hamilton, Ship Material Readiness (Washington, D.C.: The George Washington University, 1962), pp. 55-61.

Navy maintenance and material management. This survey, which covered managerial activities responsible for both aircraft and shipboard maintenance and material, was conducted during the Fall of 1963. This "User Survey" information was compiled, edited, and computer processed at The George Washington University and initial analysis was conducted in February, 1964, by Project research personnel together with representatives of cognizant Navy Bureaus, the Fleet Work Study Groups, and the Office of Naval Research.[5] The results of this analysis were formulated into a recommended Integrated Navy Ship Maintenance and Material Information System.[6] Procedures were recommended for data collection, processing, and dissemination. These procedures were to become the basis for what is now the Maintenance Data Collection Sub-System (MDCS) of 3-M.[7] MDCS was introduced to the fleet commencing in late 1964--approximately one year after the first ships received the PMS program. By mid-1970, 100% of the active fleet ships had converted fully to MDCS; 98% of the active fleet currently have PMS implemented and that sub-system is estimated to provide coverage on 95% of the fleet's maintainable equipment.[8]

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[5]Logistics Research Project, Survey of Information, pp. 3-11.

[6]James E. Hamilton, An Integrated Navy Ship Maintenance and Material Information System (Washington, D.C.: The George Washington University, 1965), pp. 1-43.

[7]James E. Hamilton, Suggested Procedures for an Integrated Information System (Washington, D.C.: The George Washington University, 1965), pp. 1-67.

[8]C. M. Benton, private interview held at the Office of the Chief of Naval Operations (Op 433), Washington, D.C., December, 1970.

3-M Overview

The Shipboard 3-M System, as revised through early 1971, is officially defined as an "integrated management system" which ". . . provides for orderly scheduling and accomplishment of maintenance and for reporting and disseminating significant maintenance related information." Its two sub-systems, PMS and MDCS, are said to form ". . . the nucleus of a shipboard maintenance program which can contribute significantly toward achieving improved fleet readiness with reduced expenditure of resources."[9]

The Maintenance and Material Management (3-M) Manual (OPNAV 43P2) describes specific system objectives as they relate to the assistance of operational and technical commanders toward achieving the goal of optimum Fleet readiness utilizing available resources. Six such specific objectives are identified:[10]

a. Define and achieve uniform maintenance standards, criteria, and procedures.

b. Assist operating forces by promoting effective utilization of available manpower, material and maintenance opportunities and by reducing the total administrative burden on maintenance personnel.

c. Document the requirements for and the accomplishment of maintenance, and the utilization of maintenance assets.

d. Increase knowledge of current ship configuration and identify desirable changes to existing configuration or improvements in new ship configuration design, through information gained by documenting maintainability and reliability experiences.

e. Improve maintainability and reliability of equipments and systems through uniform maintenance disciplines

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[9] U. S. Department of the Navy, Maintenance and Material Management (3-M) Manual (OPNAV 43P2) (Washington, D.C.: Office of the Chief of Naval Operations, 1970), pp. 1-2 to 1-4.

[10] Ibid.

and improved engineering practices, identification of essential design changes to existing equipments/ systems, and documentation of experience data of value in new equipment/system design.

f. Accurately identify the cost of maintenance in terms of manpower, material and funds, and reduce these costs through maintenance efficiencies and management effectiveness.

Can the concepts and objectives listed above be reconciled with the goals of any set of previously developed preventive maintenance theories? This question--central to our research--will be addressed in detail in the next chapter; at this point, however, a few preliminary observations may prove useful. The term "integrated management system" (italics mine) raises the obvious question: What is integrated? It is believed by this author that the reference is not to the integration of action by the universal application within the surface naval community, but rather that the system is internally integrated through the interface which must exist between its two sub-systems, PMS and MDCS.

This notion of system integration is reinforced by the wording of the quoted objectives in sub-paragraphs (e) and (f) above. Reference is made to the improvement of engineering practices (presumably including preventive maintenance) and the reduction of costs through maintenance efficiencies and management effectiveness. Does this mean that after application of uniform preventive maintenance standards in the PMS sub-system, the MDCS sub-system provides the necessary feedback of failure and readiness data necessary for system alteration and improvement? Can we validly describe a partial intent of the total system to provide a cybernetic loop for the

monitoring of system performance and the correction of deficiencies? This hypothesis might be simplistically viewed as a closed system such as that shown in Fig. 10.

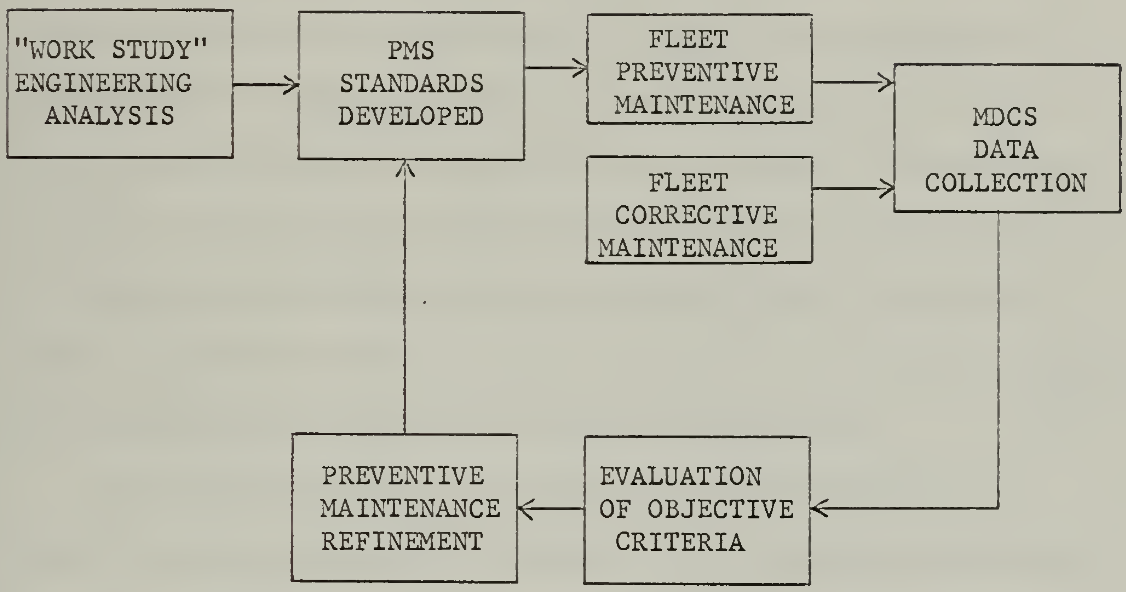

Fig. 10.--Hypothesis of 3-M Integration

To study these questions, it is necessary to examine the 3-M sub-systems, analyze their objectives, operating procedures, and inter-relationships. In the next section we will consider first the operation of the PMS Sub-System; attention will then be given to the MDCS Sub-System; and finally to the extent of interaction, feedback, or integration.

The Planned Maintenance Sub-System (PMS)

In a terminology section of the 3-M Manual, preventive maintenance is defined as "those maintenance actions performed on equipment to maintain uninterrupted operation within design characteristics or to detect and/or prevent failures before they occur." Planned Maintenance is then defined as "preventive maintenance accomplished on a regular periodic basis."[11] The caveat "within design characteristics" is important, for it permits failure characteristics which do not exceed those which can be computed from the reliability and maintainability equipment design standards. Perfect equipment operation is not visualized; but a minimum standard for the preventive maintenance program is established.

The PMS Sub-System is described as a program which will provide each ship, operating department, and individual maintenance supervisor (Work Center Supervisor) with the necessary planning, scheduling, and control tools to effectively implement a preventive maintenance policy consistent with the overall 3-M objectives. The specific objectives of PMS are expressed as designed to:[12]

a. Reduce complex maintenance to simplified procedures, easily identified and managed at all levels.

b. Define the minimum planned maintenance required, schedule and control its performance, describe the methods and tools to be used and provide for the detection and prevention of impending casualties.

c. Forecast and plan manpower and material requirements.

d. Plan and schedule maintenance tasks.

e. Estimate and evaluate material readiness.

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[11] Ibid., p. 3-2.

[12] Ibid., p. 3-1.

f. Detect areas requiring additional or improved personnel training and/or improved maintenance techniques or attention.

Benefits to be derived from PMS are described in the manual and these can be summarized as:

1. Increased Reliability

2. Increased Economy

3. Better Planning

4. Simplified Records

5. Improved Management and Maintenance "Morale"

6. Training Opportunities

7. Continuity of Maintenance Control[13]

The principal tools of the PMS which contribute toward the attainment of the described objectives and associated benefits are:

1. PMS Manual (OPNAV 43P1) containing Maintenance Index Pages (MIP's) (OPNAV 4700-3)

2. Cycle Schedules (OPNAV 4700-4)

3. Quarterly Schedules (OPNAV 4700-5)

4. Weekly Schedules (OPNAV 4700-6)

5. Maintenance Requirement Cards (MRC's) (OPNAV 4700-1)

Samples of each of the above can be found in Exhibits 1-4 of Appendix A and may be useful for reference in the brief description which follows.

Each individual work center aboard ship is provided a PMS Manual which contains necessary basic instructions and a group of MIP's--one each for every different type of equipment (pump, motor, radar set, etc.) for which preventive maintenance actions have been developed.

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[13] Ibid.

An MIP lists the PM checks by periodicity and provides information on the skill level (rate and rating), manpower, and time required for each PM action as well as correlating related PM actions so that they may then be scheduled concurrently. The cycle, quarterly, and weekly schedules then provide the means for departmental and work center managers to schedule these maintenance actions with increasing precision ranging from a selection of the quarter assignment (within a 12 quarter, 3 year overhaul cycle) to the specific assignment of a repairman or repair team to a specific action on a given day of the current week. Finally, the maintenance action is performed in accordance with the standardized procedures of the MRC which is kept in the work center with the weekly schedule. As shown in the sample (Appendix A, Exhibit 4), an MRC provides additional detailed data including safety precautions, tools and material required, and "Work Study" developed maintenance action procedures. The accomplishment, or non-accomplishment, of scheduled PM actions are annotated on weekly and quarterly schedules and the latter are retained on board as a record of planned maintenance accomplishment.[14]

With the brief understanding of PMS provided above, three questions emerge in an attempt to relate this 3-M sub-system to theoretical preventive maintenance models and policies:

1. How is a specific type of equipment chosen for inclusion under the PMS?
2. How are the MRC actions determined?
3. How is the periodicity of each MRC calculated?

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[14] _Ibid._, pp. 3-1 to 3-30.

This paper's research has indicated that definitive answers to the above questions are surprisingly difficult to obtain. For most shipboard equipment, the relevant official publication is the Planned Maintenance Development Specification Manual of the Naval Ship Systems Command (NAVSHIPS 0900-039-1010). "It prescribes policy and procedure for the development of Maintenance Index Pages, Maintenance Requirement Cards and support documentation."[15]

The Development Specification Manual classifies maintenance into five types:[16]

a. Safety - care to avoid conditions that endanger personnel or stress material beyond reliability;

b. Operating - immediate and constant tasks that cause equipment to do the job designed to do;

c. Preventive - scheduled periodic tasks of care and inspection designed to prevent a breakdown or prolong the life of equipment;

d. Corrective - unscheduled tasks required to restore equipment to an operational status after a breakdown or impending failure is discovered;

e. Overhaul - complete disassembly and reconditioning to a like-new status.

The manual then notes that these types of maintenance will generally be accomplished through two classes of tasks: Care and Inspection. Care is defined as "adding or taking away something" (lubrication, replacement of worn parts, etc.) and Inspection is described as "the use of the senses alone or in conjunction with a tool" (inspect safety devices, examine visually for tightness, measure clearances,

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[15] U. S. Department of the Navy, Naval Ship Systems Command, Planned Maintenance Development Specification Manual (NAVSHIPS 0900-039-1010) (Washington, D.C.: Naval Ship Systems Command, 1969), p. iii.

[16] Ibid., p. 3-1.

etc.).[17] We can construct a matrix to indicate the possible combinations of this two-dimensional classification.

Tasks \ Types	1 Safety	2 Operating	3 Preventive	4 Corrective	5 Overhaul
A. Care	POSSIBLY PREVENTIVE MAINTENANCE	ROUTINE SERVICING	PREVENTIVE MAINTENANCE	REPAIR	PREVENTIVE MAINTENANCE OR REPLACEMENT
B. Inspection	PREVENTIVE INSPECTION	OPERATIONAL SYSTEM MONITORING	PREVENTIVE MAINTENANCE OR INSPECTION	INVESTIGATION PRELIMINARY TO CARE OPPORTUNISTIC REPLACEMENT	PREVENTIVE MAINTENANCE OR INSPECTION

Fig. 11.-- Classification of Maintenance

The manual notes that PMS will concentrate on type 3 maintenance but may include more extensive overhaul action (type 5). Types 1 and 2 are described as tasks of at least daily frequency and may be included in PMS. Corrective maintenance (type 4) is unscheduled but may be covered by a situational MRC which is essentially an "as required" periodicity. The matrix, Fig. 11, is annotated with suggested terminology for related theoretical PM policies.

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[17] Ibid.

In discussing the PMS "philosophy," it is stated that:[18]

> PM tasks are deliberate and regulated care, coupled with intervals of recorded inspection (that portray a trend or a deviation from operating standards), to maintain a materially ready condition. Any deviation in performance must be presented to the controller in sufficient time to allow the care to be altered, thus eliminating the breakdown and a later need for corrective maintenance. . . . A usable record of accomplished PM and accomplished corrective work (not covered by PM) is necessary in order that a history be accumulated to justify the relaxing of some requirement or the establishment of new ones. This history must be relayed to a central agency within a command so that all like activities can benefit through method improvements, generated as a result of the feedback, and decisions can more rapidly be made.

Later, in the instructions covering the selection of a periodicity for an MRC under development, the proper choice is said to be that:[19]

> which is the minimum amount of expenditure (manhours/material) for the equipment operating at an expected average demand and within an environment which would prevail for the majority of like items. . . . The intent is that the major population of the fleet should not be levied with periodicities adjusted to assure reliability under exceptional conditions.

The following summary points appear relevant to the limited survey of the PMS sub-system conducted, its methodology, and relationship to theoretical concepts previously developed:

1. PMS is essentially a management engineering approach to the problem of optimum work standardization and simplification. It uses accepted systems and procedure techniques to study work, improve efficiency, and reduce waste.

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[18] Ibid., pp. 3-2 to 3-3.

[19] Ibid., Chapter 5.

2. PMS development is a judgmental process which utilizes a wide-variety of source data including historical maintenance and failure information, but this development is not part of a continuing feedback of information and refinement.
3. PMS is conceived and developed for aggregate systems and equipment. It seeks to specify a standard "lowest common denominator" toward meeting design standards for a vaguely defined "normal" or "majority" portion of the total population.
4. PMS acknowledges the need for a management information system to collect data for feedback and system improvement, but it does not identify such a system or explicitly describe a formal interrelationship. Specifically, PMS is able to stand alone without dependence on the sister MDCS sub-system.

From the PMS side of the 3-M system, it is difficult to sight the anticipated interface with MDCS; it is now necessary to investigate from the other side and see if the fragmentation is as pronounced from the vantage point of the information system.

The Maintenance Data Collection Sub-System (MDCS)

The MDCS has been the more volatile of the two 3-M sub-systems. It has undergone the greatest revision in terms of both system content and format, experienced the widest criticism, and probably sparked the greatest abuses in overall 3-M operation and evolution. At the

time of this research, MDCS is undergoing the latest in a continuing series of reviews and studies, and, at least for some interim period, has been curtailed to the extent of reducing fleet reporting requirements by 40%.[20]

The scope of the sub-system has been partially described as providing:[21]

> a means for maintenance personnel to record information pertaining to preventive or corrective maintenance actions. The system uses coded data elements for recording much of this information in order to standardize the data collected and to facilitate its processing and use. The failure and corrective action information recorded on the maintenance action documents, and the material usage information recorded on associated supply documents, is retrievable through this system for engineering analysis and maintenance history.

MDCS has, through its seven year history, collected a changing mix of maintenance information including:

1. Preventive (PMS) Maintenance Actions Performed
2. Preventive Maintenance Actions Not Performed (exception reporting)
3. Corrective Maintenance Actions Performed
4. Deferral of Maintenance Actions (Preventive or Corrective) due to operational or resource requirements/limitations
5. Completion of Deferred Maintenance Actions
6. Requests for Work Assistance External to the Reporting Organization

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[20] See Appendix D.

[21] Department of the Navy, OPNAV 43P2, p. 4-1.

7. Requests for Work Assistance Internal to the Reporting Organization
8. Material Inspection Discrepancies
9. Exception Time Reporting for Maintenance Activity Manpower Utilization
10. Material Usage Data Associated with Maintenance Actions.

Collection of data records such as those above has been from fleet units (individual ships), intermediate activities (repair ships and tenders), and maintenance depots (ship repair facilities and shipyards). By 1971, the first eight types of records had been incorporated into a single multi-purpose documentation form, OPNAV FORM 4790/2K shown as Appendix B. Previously, a variety of hand-coded forms had been used depending upon the type of maintenance action. Although no longer practiced, certain fleet activities have occasionally utilized pre-punched IBM cards to report the accomplishment of standard PMS actions in an effort to reduce manual form preparation. The current document provides a variety of alternative coding schemes. Data fields vary for different types of actions but a representative sample for the reporting of a corrective maintenance action include:[22]

1. Organizational identification (to the reporting work center level aboard ship)
2. Equipment identification (including specific identification where more than one such equipment is maintained by the organization)

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[22] Ibid., pp. 4-9 to 4-24.

3. The nature of the first indication of equipment malfunction
4. The operating environment in which the malfunction was discovered (Operating, Starting, Stopping, Inspection, etc.)
5. The date of malfunction discovery
6. The operational availability of the equipment after discovery of trouble
7. The action taken to complete repair
8. The number of manhours (to the nearest 1/10) required for repair
9. The rate/rating of the senior repairman
10. The date repairs are completed
11. The status (operational) of the equipment after maintenance action completion
12. The activity's best determination of the cause of the equipment failure or malfunction.

Additionally, provision is made for additional time data for equipment with installed meters or counters to record active maintenance time, troubleshooting time, and actual meter readings.

Since 1969, there has been little required reporting of preventive (PMS) maintenance actions and documents forwarded by ships have been limited to:

1. Completed maintenance actions involving malfunction correction.
2. Deferral of maintenance actions involving malfunction correction.

3. Requests for outside work assistance.

4. Feedback reporting of 3-M system discrepancies, request for technical advice or alteration of system procedures/requirements. (Such feedback reports can vary widely from a simple ship report that it has lost an MRC and requires a replacement to a request for coverage of a newly installed system for which PMS requirements and MDCS coding data are not existent.

Source documents such as the above are prepared aboard ship, forwarded to the appropriate Type Commander, processed to varying degrees according to ADP capabilities, and finally forwarded to the MDCS master data bank at the Maintenance Support Office, Mechanicsburg, Pennsylvania. Those Type Commanders (or ships) possessing sufficient ADP processing capacity produce data products for local management use. The mission of the Maintenance Support Office (MSO) includes the responsibility in the 3-M program for:[23]

1. Operating and maintaining a central data processing center.
2. Supporting the Chief of Naval Operations in the management of the 3-M System.
3. Providing the necessary information to determine resource requirements for weapons systems, ship and aircraft material readiness, and cost and effectiveness at all levels of weapons systems.
4. Providing routine information reports to technical bureaus [System Commands] and Fleet Activities.
5. Developing and maintaining master files of 3-M data.

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[23]Chester R. Oberg, "The Role of the Maintenance Support Office," U.S. Naval Institute Proceedings, Vol. 95, No. 5 (May, 1969), p. 144.

6. Developing techniques for the coordination of 3-M data with inventory control points, using such files as ship's configurations, allowance lists, load lists, and wage rates.
7. Providing information on the maintenance of the 3-M System.

There are literally hundreds of output products produced by MSO. These include Type Commander Maintenance Analysis Reports (classifying maintenance actions, their manpower utilization, and material costs by activity), Composite Cost Analysis Reports, and Ship's Material History Reports (essentially the periodic updating of a cumulative transaction file for each ship--prepared monthly with semi-annual, and annual summaries on request.) MSO has an Operations Research Division. This branch is concerned primarily with the validity of all MSO data and uses various analytical techniques to monitor the "quantity, quality, and timeliness"[24] of MSO inputs and outputs. No evidence has been found to indicate that this Division has ever attempted to apply any of the theories presented in the preceding chapter. Further, this Division is not in direct liaison with outside activities, particularly those involved in the development of shipboard PMS software (Naval Ship System Command, Fleet Work Study Group, etc.).

All indications seem to reveal only the loosest of connections between the 3-M sub-systems in terms of the feedback of data and system refinement. There exists a Feedback Report system, but it is based upon individual command initiation, not data analysis or model programming. Maintenance data is processed and returned to

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[24] Ibid.

the fleet as well as to technical commands, but the existing programs are not utilized to attempt a refinement via analytical techniques. Finally, PMS, while highly successful as an example of work simplification and standardization, seems to offer little improvement in the dynamic capability to analyze increasingly massive quantities of experiential data and adjust to changing conditions.

Perhaps it is now possible to redraw a new view of the 3-M system showing that it is not accurately a closed-loop system but only loosely circular as in Fig. 12.

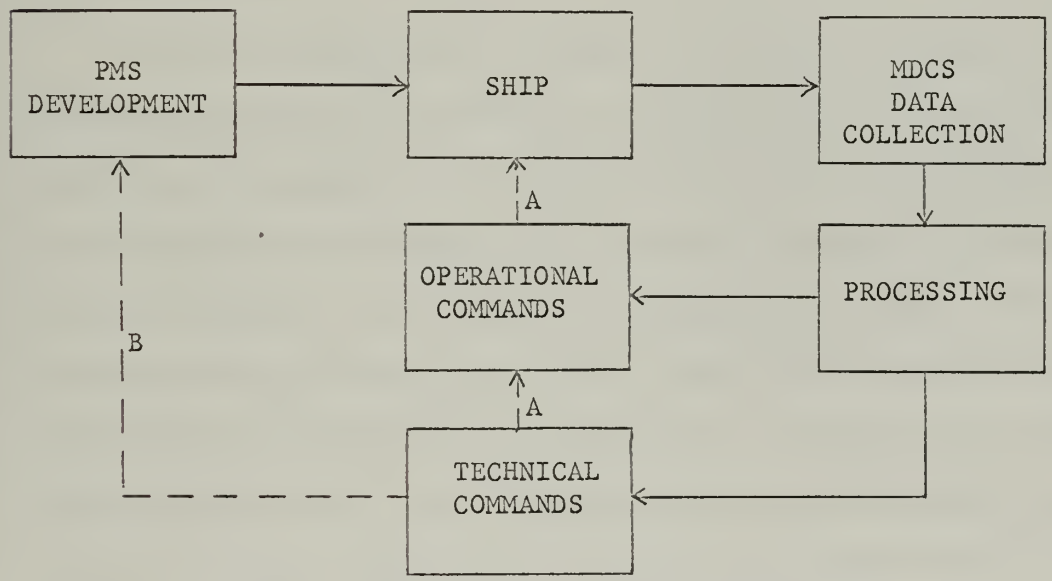

Fig. 12.--Degree of Actual 3-M Integration

It is argued that the present system only vaguely defines the nature of connections A and B. Further almost all data products are oriented toward the loose closing of the loop via path A, rather than via path B which would encompass the real integration of PMS and MDCS. Valid explanations for this hypothesis are searched for in the next chapter.

CHAPTER IV

THEORY APPLICATION FOR 3-M

We have, to this point, accumulated a base of information concerning both theoretical and actual policies of preventive maintenance. It now appears plausible to examine such congruence as exists between the two; develop a rationale to explain observed divergence; and investigate the extent to which formal theoretical models have been employed in the shipboard 3-M system.

Like the Preparedness PM model, the 3-M system appears to have the primary objective of achieving a defined level of output (which might best be thought of as designed contribution to readiness) with the minimum resource utilization. This does not imply that the 3-M system is analogous to the strict cost-minimization model. Costs and benefits are both involved, and with a given level of required benefit, effectiveness is maximized by the adjustment of system inputs that achieves minimum cost. In an economic sense, readiness may be thought of as the "revenue" accruing to the system, and effectiveness is therefore comparable to the "profit" which is to be maximized.

Both the theoretical models presented and the 3-M system operation described recognize and deal with the stochastic nature of the maintenance environment. MDCS analysis presently includes a program which periodically analyzes selected equipment failure data to check for the possibility of

approximation with an exponential probability distribution.[1] As has been previously suggested, the results of such analysis are, however, more typically forwarded to equipment design and procurement activities (for use as reliability and maintainability data) than those activities charged with the responsibility of updating PMS requirements and periodicities.

Much of the divergence observed between the models and the 3-M practice can be traced to the real world actualities which require abandonment of the useful, but often artificial, assumptions of the simpler theoretical policies. PMS, for example, recognizes that equipment failure is not always an instantaneous process, but rather often characterized by gradual deterioration and accompanying performance degradation. Further, it seeks to provide for a frequency of inspective maintenance which will detect such deterioration before the final "failure" is observed by operating personnel.

In the first cost-minimization model, the needed cost data was given as that of before-failure PM and after-failure corrective maintenance. One basis of the PMS "philosophy," however, is the degree of variability of the latter after-failure cost. Even disregarding the effect on material readiness, the nature of the shipboard maintenance environment is such that corrective costs are a function of variables such as ship location, operational employment, tempo of activity, personnel manning, etc. PM "costs" may also exhibit some degree of

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[1]Private interviews with the staff for Program Development of the Maintenance Management Branch of the Fleet Maintenance Directorate of the Naval Ship Systems Command Headquarters, Arlington, Virginia, December, 1970.

variability--in any event, PMS scheduling flexibility is designed, in part, to allow maintenance managers the ability to capitalize on periods of lower cost factors.

In the most basic comparison, it appears that the principal difference between the approaches is developed from the theoretical assumption that each hour of equipment operation is equivalent in terms of incremental utility. The operable state of shipboard equipment does not, however, make a constant contribution of utility to the activity or its mission. That is to say, the contribution to material readiness of a particular system or component is variable with time and place. This contribution is, of course, also interrelated with the operational capability of other components or systems. Such variability with time and space and the integration of total system effectiveness have been the characteristics which have spurred research into the development of a meaningful index of a ship's material readiness.

The concept of material readiness and its impact on policies of preventive maintenance need not be considered as applicable uniquely to a military environment. Similar problems could be developed and stated for industrial situations. The notion of readiness has received attention in areas such as NASA's manned space flight program.[2] Our specific task is now to examine its meaning in the Navy and the impact of such a determination on the reconcilliation between theoretical PM and the 3-M system.

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[2] R. B. Carpenter, Jr., "Space: Manned Interplanetary Travel, Part 5 of 'Reliability and Maintainability,'" Mechanical Engineering, (June, 1966).

Material Readiness

In a contract project for the Office of Naval Research previously referred to, the Logistics Research Project made one of the earliest investigations into the definition of material readiness. The report of this research postulated that overall ship readiness could be categorized into five factors:[3]

Personnel

Material Supply

Operational Availability

Obsolescence and

Deterioration

This research, which stressed that material readiness was a measure of the interaction of the latter two factors, then formulated a model of a ship's material readiness such that an index measuring this capacity was defined:

R_{sm} = Ship Material Readiness Index

The index was seen to be a function of the influences of ship design, condition, reliability, and time. Specifically, where

D_o = original design of the ship when she first enters service;

$D_c = D_a + D_x$, with D_a = change in D_o due to added features (+ or −),

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[3]J. E. Hamilton, Ship Material Readiness, (Washington, D. C.: The George Washington University Logistics Research Project, 1962), pp. 3-4.

D_x = change in D_o due to excised features (+ or −);

C = The condition or measure of the capacity of the material to perform, in use or action, to the limits for which it was designed;

E = A measure of dependability or reliability for continued functioning;

T = The period for which a decision is to be performed;

T_a = The length of time, after a decision, to accomplish a change (as for D_a, D_x above);

T_e = The length of time of expected continued reliability;

T_r = The length of time it will take to make a repair;

Then

$$R_{sm} = f(D_o, D_c, C, E, T, T_a, T_r, T_e) \ .$$

The research concluded that:[4]

> This expression is offered as a complete statement of the things which must be considered, as applicable, to the material readiness of any individual ship. Each of the factors must be developed to fit the situation (normally time defined) for which ship material readiness is to be determined.

Although this LRP paper has never been formally adopted by the Navy, it is interesting because it immediately predates that project's developmental work for the MDCS sub-system. Indeed, the multiple factors which are shown to influence the composite index (and by inference, any system or equipment separately analyzed) are all available from reporting requirements of the current MDCS.

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[4] *Ibid.*, p. 63.

In his survey of the concept of readiness, McVoy notes a more recent (1969) proposal for a Military Condition Index (MCI)--also a product of the LRP:[5]

> The general scheme of the George Washington model calls for a structuring of a ship's material as "line elements" within "function" groups which, in turn, make up "departments." A block of 100 points was first assigned to each department and these points were, in turn, prorated among the respective functions according to the importance of each function, then the line elements received a further prorating of the points allotted to the function.
>
> A multiplying process was conducted next to obtain the Military Worth [MW] evaluation of each line element, function, and department. These were to total 10,000 points for a ship. Thus,
>
> $$\Sigma MW_{elem} = 10{,}000 \text{ points}$$
> $$\Sigma MW_{func} = 10{,}000 \text{ points}$$
> $$\Sigma MW_{dept} = 10{,}000 \text{ points}$$
>
> A verification process has been in effect on this breakdown utilizing feedback information from grading data provided by the Board of Inspection and Survey [INSURV] for individual ships. The grades were . . . accorded numerical values of 5, 4, 3, 2, 1 . . . . These factors were treated arithmetically as follows: . . .
>
> $$MCI = \frac{\Sigma MW_{elem} \cdot \text{Grade}}{MW_{func}}$$

As McVoy notes, this methodology contains two significant judgmental elements--the determination of Military Worth point allocation and the grading conducted by INSURV. Further, although INSURV discrepancies are now reported through the MDCS, there is currently no provision for the sub-system to incorporate grading fields down to the "element" level. For both of these reasons, it would seem unlikely that this latter LRP index scheme can usefully be incorporated as a link between the 3-M system and a quantitative model.

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[5] McVoy, Material Readiness, pp. 70-72.

The most recent proposal to the Chief of Naval Operations for a material readiness index has been developed by the aforementioned Captain James McVoy. Working for the Ship Material Readiness Division of the Office of the Chief of Naval Operations, McVoy has developed a quantitative technique based partly on previous work conducted by the Weapon-Systems Effectiveness Industrial Advisory Committee (WSEIAC) to the Air Force Systems Command. The WSEIAC model describes Weapons System Effectiveness (WSE) as: "WSE = f(A,D,C)" where:[6]

A = Availability,	a measure of the condition of the system at the start of a mission, when the mission is called for at an unknown (random) instant of time.
D = Dependability,	a measure of the system condition during the performance of the mission; given its condition (availability) at the start.
C = Capability,	a measure of the results of the mission, given the condition during the mission.

In other words, $WSE = A \times D \times C$ where

A = Probability (System is Up)

D = Probability (System stays Up | System is Up)

C = Probability [Mission Accomplishment | (System Stays Up | System is Up)]

[6] Ibid., pp. 20-25.

According to McVoy, material readiness is a measure of the relative effectiveness of a weapons system (or other ship system), that is a measure R = Probability (Effectiveness – actual ≥ Effectiveness – required), or alternatively there is some factor, k, a measure of readiness such that:

$$\text{Effectiveness}_{\text{Actual}} = k \cdot \text{Effectiveness}_{\text{Required}}$$

The definition of availability, dependability, and capability as the stochastic variables comprising system effectiveness has achieved considerable attention in the literature. Blanchard and Lowery, have, for example, used them in their conception of a hierarchy of trade-off parameters linking the notion of design maintainability to overall system cost-effectiveness. This ascending order of parameters is shown in Fig. 13.

In an earlier work on the subject of designed maintainability, Goldman and Slattery describe a similar construction of the interrelationship of the components of system effectiveness. In all such works researched, preventive maintenance, if mentioned, is treated peripherally as a scheduling set of design decisions—one of the elements of maintainability. Considerable attention to this equipment design aspect of preventive maintenance has been given by the Logistics and Operations Planning Operation (TEMPO) of the General Electric Company.[7] Navy contracting involvement in TEMPO investigations has

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[7] A. S. Goldman and T. B. Slattery, Maintainability: A Major Element of System Effectiveness, (New York: John Wiley & Sons, Inc., 1964), pp. 1-26.

been concentrated in the area of the Fire Control and Guidance Systems for the Polaris project.[8]

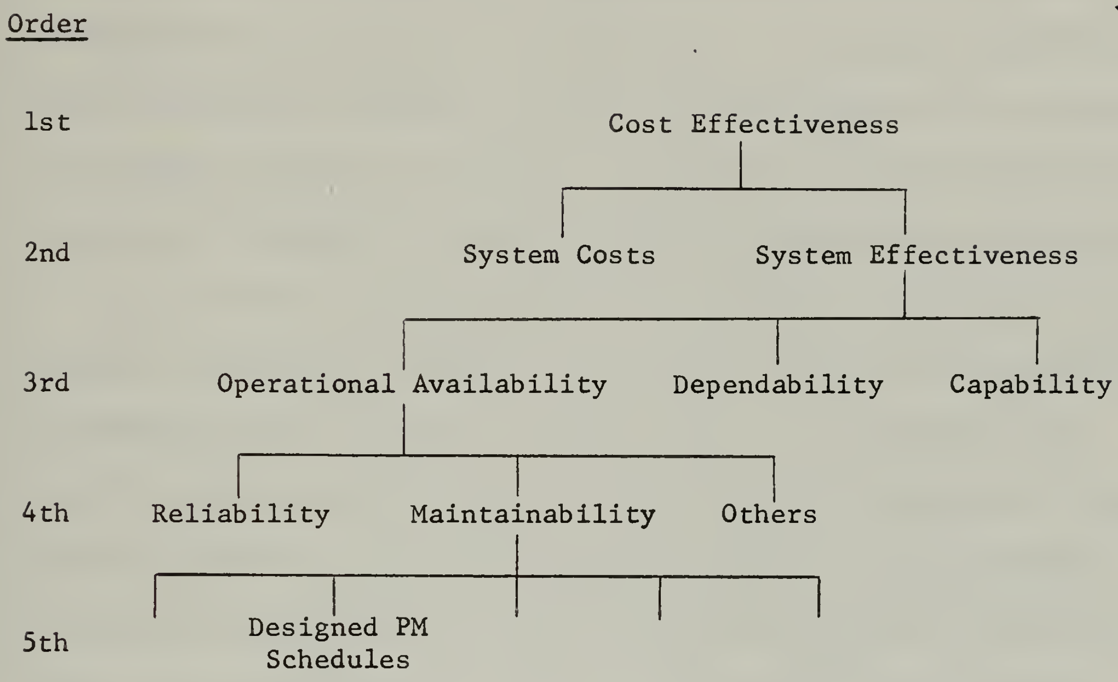

Fig. 13.--Order of Trade-Off Parameters[9]

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[8]Department of Defense recognition of this interrelationship is expressed in the standards and requirements of two directives which quantify M (maintainability): DOD Directives #3200.6 of 7 June 62 and #4100.35 of 19 June 64. A specific military specification of the Naval Ship Systems Command (Mil-M-23313) on the "Maintainability Requirements for Shipboard and Shore Electronics Equipment and Systems" is illustrative of such standardization:

> Maintainability Requirements. The procuring activity will specify an equipment repair time (ERT) in the detailed equipment or systems specification. The design of the equipment or system shall be such that the geometric mean of all active repair time intervals required to repair independent failures shall not exceed the specified ERT. Compliance with this requirement will be verified in the final design stage, and in the pre-production and production stages.

[9]Benjamin S. Blanchard and E. Edward Lowery, Maintainability (New York: McGraw-Hill Book Company, 1969), p. 119. Fig. 13 is adapted from their Fig. 7-1.

The discussion of preventive maintenance in the context of maintainability and equipment design digresses somewhat from our consideration of an operational maintenance policy, but is valuable to highlight the perspective of this thesis. The broader, operational, view of preventive maintenance allows its consideration not as merely a "5th order" parameter as in Fig. 13, but also as interrelated with each of the "3rd order" parameters which determine system effectiveness.

In a separate paper prepared for the Office of the Chief of Naval Operations, McVoy has developed a calculation technique for determining an individual ship's material readiness index. This involves the analysis of the essential systems of the total ship system, their subsystems, supporting primary and redundant equipment; the assignment of an exponential grading methodology through the analysis of both quantitative and qualitative data; and a calculation procedure involving standardized tabulation charts and derived nomographs for determination of the critical variables (availability, reliability, etc.). Information is provided on the characteristics of specific failure data. It is not necessary for our present purpose to examine the technique in detail, but it is useful to note that among the sources of data utilized are Casualty Reports, INSURV discrepancies, and 3-M data.[10]

McVoy does not elaborate on the exact nature of the 3-M data which he envisions to be useful nor does he address the question of this paper regarding the application of his computed readiness index toward improvement of preventive maintenance practice. Nonetheless, the

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[10] J. L. McVoy, <u>The Analysis and Measure of a Ship's Material Condition and Readiness</u>, (Washington, D. C.: Office of the Chief of Naval Operations (Op-433F-2), 1970), pp. 63-68.

opportunity which exists merits additional attention and research. There is indication that a general standardized technique for the measurement of ship material readiness is being refined and may soon be adopted for the Navy. Such a methodology will be able to utilize existing MDCS data and undoubtedly suggest improved formats for its collection. It may also provide some of the necessary linkage between the two 3-M sub-systems such that PMS development can move in a direction away from the judgmental approach to one employing quantitative procedures of Operations Research allowing at least some of the following advantages to develop:

1. Elimination of Preventive Maintenance Requirements which do not contribute to the objectives of 3-M.
2. Adoption of new PM where it will add toward the achievement of 3-M goals.
3. Refinement of PMS requirement periodicities to provide the optimum contribution.
4. Improved accuracy and speed in the feedback of 3-M information due to the use of computer calculation of the quantifiable system variables.
5. The possibility of segregating 3-M data by specific activities or groups of activities so that a PMS package can be individually tailored for a unit not only on the basis of its unique equipment configuration but also on the basis of the uniqueness of those factors contributing to readiness aboard a specific ship.
6. The morale boost so obviously needed by fleet maintenance personnel which will accrue when maintenance data submitted at the work center level is

returned in the form of a recommendation for improvement of preventive maintenance to benefit the individual ship rather than as a mere tabulation of the work which the personnel are well aware of having expended.

A New Integration for the 3-M System

It has just been suggested that a viable measure of material readiness may aid in bridging the existing gulf between PMS and MDCS. Such a notion may be true, but it must be stated in a more comprehensive context and subjected to certain limitations. A more complete statement of the idea being developed is that Operations Research (specifically the preventive maintenance models) is the vehicle for integrating the 3-M system and the measurement of material readiness provides an alternative criteria for policy determination using the PM models.

As an example, it may be possible in some instances to redefine the right side of the cost minimization model presented in Chapter II. This value, previously defined as $\frac{B}{A-B}$ might now express a readiness relationship where:

A = Loss of material readiness per unit after failure (during corrective maintenance period), and

B = Loss of material readiness per unit before failure (during preventive maintenance period).

The model could still be solved as before to determine the optimum PM interval, T.

It will not be possible to utilize such a readiness criteria for all equipment presently covered by the PMS sub-system. PMS coverage has been extended to almost all maintainable shipboard equipment. Much of this equipment is located in shipboard systems which will not, and should not, be measured by a military readiness assessment of material. While it is possible to argue that all equipment placed aboard a naval ship must ultimately contribute in some measure to the military capabilities of the ship, some practical limits must be established.

The record selectors (juke boxes) provided for the crew's recreational areas may enhance overall ship readiness by their positive contribution to morale. But we will probably wish to maintain such equipment on a cost-minimization policy; not on the basis of aggregate material readiness. Similarly, a steam press in the ship's laundry (operated on a 24 hour basis) might best be evaluated by a policy which attempts to maximize operating time without regard to calculations involving availability, dependability, and capability. Other examples could be cited, but the basic observation must be that there will be different populations of equipment and ship systems for which varying criteria and PM policies can be adopted.

A more fundamental limitation of a compound criteria such as material readiness is that a policy derived to maximize this quantified measure will provide only a sub-optimization of the ultimate organizational objective. Commanding Officers of ships are responsible for the composite function of ship readiness of which material readiness is but one component. To the extent that maximization of material readiness detracts from the proper mix of resources to other components, such as

personnel or supply readiness, the sub-optimization achieved will not produce the best total ship system effectiveness. This deficiency exists, however, at all levels of defense management and its treatment is deferred as beyond the scope of the present work.

The application of theoretical preventive maintenance models to the 3-M system can involve more than the determination of maintenance frequency. Indeed, the determination of PM periodicity may be the most difficult of the theories to implement within the existing system. This difficulty, whether for preventive maintenance or preventive inspection, is principally the result of criteria determination. Other operations research concepts in Renewal Theory may be easier to recommend and apply for the 3-M system, particularly the techniques of the PMS sub-system. Specifically, attention will be given to utilization of group replacement and opportunistic inspection/maintenance policies.

It has been the experience of this author that group replacement policies, where practiced in the fleet, are more typically the result of local initiative as opposed to centralized guidance. Further, most of the group replacement actions which have been observed are justified on engineering beliefs rather than economic considerations. Finally, specific PMS maintenance requirements which direct group replacement are rare. These personal observations of the subject were confirmed by representatives of the Naval Ship Systems Command during research interviews.[11]

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[11]Private interviews, Mr. H. T. Felsen (Navships 04113) and others, held at Arlington, Virginia, January, 1971. Also a briefing by Capt. James McVoy and members of his staff, Naval Ship's Engineering Center, Hyattsville, Maryland, January, 1971.

A simple example may aid in illustrating the above observation. A PMS requirement common to all naval ships is the daily inspection and testing of the navigational lights electrical system just prior to sunset. This procedure, which evolved long before the 3-M system, requires that an electrician check the satisfactory operation of all such lights, correct any noted deficiencies, and report such action to the Officer of the Deck. The most common deficiency is, of course, a defective bulb which must be replaced. Some of the lights are readily accessible, but others located on the ship's mast require a considerable expenditure of time and effort to replace. These masthead lights must be reached by climbing the ship's masts--a hazardous job at sea involving many safety precautions involving safety equipment, extra men, and the securing of critical electronic equipment (radios and radars) which temporarily degrades the ship's military readiness.

It seems logical to assume that the rational basis for the inspection requirement is based upon the failure characteristics of such lights exhibiting increasing wear-out over time. The individual cost of replacement bulbs is very small in relation to the other costs of the repair operation. This is, in fact, the classic group replacement case quoted from Ackoff and Sasieni in Chapter II.[12] Yet, except where individual managerial initiative aboard ship adopts such a group replacement policy and instructs electricians to replace all masthead lights whenever one fails, the Navy does not provide guidance in this area.

Light bulbs on a mast, piston rings in a diesel engine, vacuum tubes in a small electronic component--all are fair examples which merit

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[12]See page 31, Chapter II.

analysis for the use of group replacement policies. As before, the use of quantitative analysis can link the failure data collected by MDCS to improvements to PMS procedures which specify group replacement where warranted. Such attention and analysis may also result in fleet acceptance of the underlying theory so that time-honored group replacement policies which are not valid can be reduced. In an era of increasing fiscal austerity for the operating forces, the practice of group replacement must be subject to economic analysis, not merely the personal intuition or convenience of the repairman.

The implementation of an analytical procedure for determining the desirability of group replacement requirements in the PMS would seem to offer an excellent means to test the managerial problems which might be encountered in a broader application of Operations Research models in 3-M System operation. Existing 3-M data could be used to select a limited number of equipment for a pilot application of such a program. MDCS feedback would be monitored, fleet reaction assessed, and analytical and administrative techniques improved in a limited use of Operations Research modeling.

A maintenance policy closely related to group replacement is known as "opportunistic inspection." Simply stated, such a policy makes the inspection of a non-monitored part conditional on the state (good or failed) of a monitored part. Research in the theory of such policies involving either the maintenance action of inspection or replacement has been extensive at the Rand Corporation with particular emphasis in the systems associated with rocket engines where only certain parts are

regularly monitored. A brief description of the basic idea of this maintenance policy is given in a Rand Memorandum:[13]

> Optimal inspection of part 0 [non-monitored] in presence of monitored part 1
>
> (1) If part 1 fails in interval $0 \leq t < n$, replace part 1 by itself.
> (2) If part 1 fails in interval $n \leq t < N$, inspect part 0, if part 0 has not failed, replace part 1 by itself, if part 0 has failed, replace both parts.
> (3) If part 0 has not been inspected in the interval $0 < t \leq N$, inspect part 0 at $t = N$ and replace if failed.

In this policy, t = age or time since the last inspection of part 0. The referenced paper illustrates a means of calculating the critical numbers n and N given the downtime costs and inspected part failure rates (assumed in this model to be exponential). The derivation of the policy closely resembles that of Barlow and Hunter presented in Chapter II.[14]

Somce measure of an opportunistic policy is currently practiced within the PMS sub-system by the identification of "related maintenance requirements" on individual MRC'S. This guidance to the shipboard maintenance manager is not a pure opportunistic policy, however, for it provides for the consolidation of two or more preventive actions (which would correspond to the notion of a policy involving parts 0 and 1 where <u>both</u> parts were monitored). Further, no detail is provided to the scheduling maintenance manager as to those conditions which would recommend the consolidation of maintenance action. Typically, these relationships are the aggregation of those lesser PM actions whose accomplishment is facilitated by the disassembly of equipment for a more extensive PM

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[13] John J. McCall, <u>Support Requirements for Opportunistic Replacement and Inspection Policies</u>, Rand Memorandum RM 3369, (Santa Monica, Calif.: The Rand Corporation, 1962), p. 4.

[14] See pages 18-21, Chapter II.

check. Finally, the determination of the related actions in the process of MRC development is principally judgmental and based upon the concepts of work simplification and duplication of effort. No quarrel is advanced against this approach, but it seems possible to expand it to include time related "opportunistic inspection" when failure data can show a correlation between separate part failures and a savings in downtime costs or other PM policy criteria.

As an example for possible investigation of an application of the above policy, it is possible to discuss two interrelated components (both monitored under PMS, but with separate and "unrelated" PM checks) which are common aboard most naval ships. These are the manual and overspeed trips provided for most large mechanical prime movers (diesel engines, steam turbines, etc). The former provides a means for operating personnel to quickly secure the equipment in an emergency; the latter is a device which automatically secures the equipment should its rotational speed exceed some design safety standard. PMS requirements for such devices are reasonably standard. They generally require the manual devices to be tested each time the unit is started or stopped and the automatic overspeed trips to be tested at a greater frequency (typically quarterly). These devices are generally mechanically interconnected and it would appear valid to assume some correlation between their failure rates. The consequences of their failure when required for emergency use, of course, can be most comparable.

It would seem reasonable for development personnel to approach such components with an attitude which will investigate the possibility of critical values n, N such that investigation of overspeed trip

operability is both periodic (N) and conditional (n) on the operability of the manual trip. Other non-monitored parts or components might warrant inclusion in this example. On a turbo-generator, there is generally an additional safety trip actuated by back pressure which is not monitored by a PM check. Perhaps it also might possess failure characteristics to warrant an opportunistic policy (although N may be in excess of the ship's overhaul cycle).

Operations Research and the Existing 3-M System--Summary

It now appears possible to suggest certain of the theoretical models of preventive maintenance for useful application within the existing form and procedures of the 3-M system. Although each of these policies, which can now be summarized, offer individually unique contributions to the improved management of shipboard maintenance, all provide the impetus toward the over-riding necessity of integrating 3-M. The current operation of the 3-M system prohibits a holistic consideration of system objectives and potentiality. The introduction of Operations Research methodology, which will both require and facilitate the integration of the work standardization and information collection sub-systems, is an excellent means of regaining a total system perspective which will allow managers to recognize the interdependency of constituent parts.

Many of the tools of Operations Research in the preventive maintenance area can be directly supplied as additional analytical steps in the development phase of PMS operation. These models would be adequately supported for a large segment of the 3-M equipment population by the existing data available from MDCS. At least the following models deserve consideration for 3-M application.

1. Simple Cost-Minimization Model

2. Maximization of Equipment Operating Time

3. Group Replacement Analysis

4. Opportunistic Inspection/Replacement Policies

Operations Research and 3-M System Refinement

For more complete utilization of the theoretical policies found in the literature, certain changes and additions to current 3-M operation and technique will be required. Additionally, continuing research is indicated to determine more precise system objectives, measurement criteria and methodology, and managerial application for the products of the System. 3-M is more than simply a management information system. It is a comprehensive management system capable of strongly influencing and improving the process of planning and control.[15] It contributes to each of the traditional "functions of management": planning, organization, staffing, directing, and controlling. Improvements in its form and content, including the possible adoption of newer quantitative techniques from Operations Research, should be examined in terms of the effects in each of these functional areas. Further, shipboard 3-M must be recognized as but one of several maintenance management systems in the Navy. Interface problems with preventive maintenance, maintenance information systems in naval aviation, nuclear power, special weapons, etc. must be examined and overall policy coordination provided at the highest levels. Finally, 3-M must operate successfully with companion

[15] H. S. Oelkers, "Effectiveness of the Navy Maintenance and Material Management System as a Management Information System," (unpublished M.B.A. thesis, The George Washington University, 1968), pp. 27-61.

management systems within the shipboard area such as financial accounting systems, inventory control systems, and personnel distribution systems.

Among the system refinements which should be investigated, the following are considered to be significant:

1. Adoption of a quantifiable definition of the concept of shipboard material readiness.
2. Development of a standardized methodology for the measurement of material readiness and the calculation of an appropriate index.
3. Improvement in the ability to isolate, identify, and measure the various "costs" of maintenance action, including specifically:
    a. A more precise measure of the costs of maintenance labor (MDCS currently identifies only the rate/rating of the senior repairman and the aggregate man-hours expended).
    b. Research into techniques which could quantify the opportunity costs of maintenance actions involving the diversion of scarce resources. This may imply, in part, the costing of degradation of material readiness.
4. Local (shipboard) identification of the time to failure since last maintenance (either in calendar or operating time as appropriate). While the requirements for shipboard record keeping and analysis would have prohibited this effort

when all corrective maintenance actions were reported, the task should be manageable under the new selected equipment reporting scheme.[16] When MDCS reporting accuracy and continuity has improved sufficiently, this task could, of course, be centralized and accomplished by computer. During the initial adoption of Operations Research modeling, however, the validity of the failure data characteristics will be the crucial element in mathematically based decisions and the feedback to the ships (of new PMS requirements) should probably be based originally on failure characteristics identified at the ship level.

5. Continuing study of the MDCS forms and the documentation effort needed to complete them with the objective of easing the admistrative burden on shipboard personnel without excessive sacrifice of timely, accurate, and usable data.
6. Investigation of maintenance action sampling techniques which might be used in lieu of a formal reporting requirement for certain applications of MDCS.
7. An attempt to construct PMS packages for ships on a systems vice equipment basis. The managerial notion of the "system" would be that of the ship itself--requirements, guidance, and control for planned maintenance would be tailored on

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[16] See Appendix D. See also "3-M System Reports Cut Simplifies Life for Fleet," Navy Times, February 3, 1971, page 5.

the basis of information concerning each individual ship's system not on the basis of combining the "averages" for a ship derived from the total population of each equipment.

8. Finally, the planning and development of an expanded educational program for maintenance managers at all levels which emphasizes the philosophy behind the 3-M System. Such a program should be separate from the functional training now offered in most aspects of 3-M operation. It would have as one goal the appreciation of the connection possible from the accumulation of data at the level to the returned benefits from that effort in terms of identifiable improvements for the shipboard manager.

CHAPTER V

CONCLUSIONS

There is a considerable body of literature in the field of Operations Research which concerns the formulation of optimal preventive maintenance policies for varying objective criteria. This base of research, which can be generally classified as a subsidiary topic of Replacement Theory, offers quantitative techniques to the manager responsible for the operation and maintenance of equipment which enable him to scientifically determine procedures which will provide the maximum contribution to selected organizational objectives. Such objectives are typically related either to the minimization of the amount of input requirements for equipment operation (costs) or the maximization of the output products from such operation or activity (benefits). Most of the preventive maintenance models surveyed are additionally based upon the stochastic characteristics of equipment operation and failure. Research has, therefore, been extensive in the statistical analysis of equipment failure data.

The Navy shipboard 3-M System has been employed in the Fleet for about seven years. It was originally designed as a means to standardize and simplify preventive maintenance practices for equipment aboard naval ships. This task has been largely accomplished through the development and operation of the PMS sub-system

which employs management engineering techniques of work study, work simplification, measurement, organizational coordination, and forms control to foster uniformity of work procedures and managerial control.

Developed shortly after PMS, the MDCS sub-system is a management information system designed from a "User Survey" to provide maintenance and material managers at all levels with the requisite data and analysis necessary to properly manage the maintenance function in the fleet operation and support areas of the Department of the Navy. Together with PMS, MDCS is officially defined as providing a 3-M system which is integrated in its approach to overall objectives.

An examination of the interface between the two 3-M sub-systems reveals only poorly defined and extremely tenuous connection. MDCS, considered as a separate entity, may be an integrated system for management information, but the 3-M System is deficient in not possessing the desired integration of its components. It appears plausible to attribute this deficiency to two related factors:

a. PMS was developed prior to, and independent of, MDCS.

b. MDCS was designed on the basis of a user activity survey which predated the implementation of PMS. Despite MDCS refinement, PMS has not become a primary user of MDCS information.

PMS provides preventive maintenance policy and procedural guidance; MDCS collects and processes maintenance data from those activities employing PMS. Preventive maintenance models from Operations Research can provide the bridge to link these currently

separate functions. The quantitative techniques of the models provide a means for improved PMS development and refinement through the feedback of information provided by MDCS. The adoption of such techniques should contribute toward overall 3-M integration and a dynamic improvement toward total system objectives.

Although the application of PM models will primarily occur at the technical bureau level where maintenance requirements are developed and reviewed, the benefits of 3-M System integration from such application should become apparent at the lowest maintenance activity levels. Currently, PMS is a contribution to the maintenance manager or worker provided by higher echelons. MDCS, however, is an extraction of time and manpower required for documentation by these same senior commands. It is not surprising that PMS has enjoyed fair acceptance and popularity while MDCS has received the bulk of the criticism from the Fleet. Maintenance personnel do not directly see the benefits derived from their documentation. An improved piece of equipment for a new class of ships is a benefit derived from MDCS, but it is not visible to the maintenance men who provided the source data. Integration of PMS and MDCS through PM modeling will, however, provide a visible cause and effect relationship to be apparent at the lowest levels. Improvements in maintenance practice will be recognized as a consequence of maintenance documentation. 3-M could become accepted as a "good" total system, not an undefinable entity composed of a "good" sub-system and a "bad" sub-system.

Implementation of the basic recommendation to utilize PM modeling to link PMS and MDCS has been suggested in four selected areas:

1. Determination of maintenance periodicity for:
    a. Preventive Maintenance
    b. Preventive Inspection
2. Group Replacement Policy
3. Opportunistic Inspection/Replacement Policies

The latter two areas appear to afford a relatively easy application of quantitative techniques in the 3-M System. Periodicity determination is also relatively easy to recommend when there exists a simple objective criterion (such as cost minimization or achieving a maximum proportion of up-time). Where such simple objectives are not available, however, the direct application of the models to the existing 3-M System is not possible. In particular, the objectives of ship and material readiness, addressed by the 3-M System, are not now quantifiable for model application. As has been indicated, other research in this area is being pursued by the Navy and will hopefully lead to broader possibilities for future model application.

This research has not addressed itself to the question of expenses involved in any possible application of quantitative modeling for 3-M System operation. Further research to determine current organizational capabilities and new requirements for the implementation of these ideas is obviously required. Neither has the present research discussed or investigated the behavioral questions associated with the substitution (however complementary) of mathematical for judgmental techniques in decision making. These factors also merit additional study before any comprehensive recommendation be acted upon.

Finally, it is hoped that the 3-M Policy Committee, which is presently conducting an extensive evaluation of the entire 3-M System for ships, will provide a vehicle for continuing dialogue on all possible avenues for system improvement and evolution. Operations Research preventive maintenance theory offers one area of contribution to this effort.

APPENDIX A

Exhibit 1 - Maintenance Index Page (MIP)

SAMPLE

SYSTEM, SUBSYSTEM, OR COMPONENT	REFERENCE PUBLICATIONS	DATE
Main Circulating Pump		May 1969

CONFIGURATION THESE MAINTENANCE REQUIREMENTS ARE APPLICABLE TO EQUIPMENT IN WHICH THE FOLLOWING CHANGES HAVE BEEN ACCOMPLISHED: NONE

SYSCOM MRC CONTROL NO.	MAINTENANCE REQUIREMENTS	PERIODICITY CODE	SKILL LEVEL	MAN HOURS	RELATED MAINTENANCE
65 9658 D	1. Operate turbine casing relief valve by hand.	D-1	MM3	0.1	None
84 5078 W	1. Sample and inspect lube oil. 2. Lubricate the speed limiting governor. 3. Turn pump several revolutions by hand, if steam is available, turn by steam.	W-1	MM3	0.5	None
85 5079 M	1. Test speed limiting governor.	M-1	MM1 FN	0.2 0.2	None
88 Q274 M	1. Inspect packing gland adjustment.	M-2	MM3	0.1	None
65 8565 Q	1. Clean sump and renew oil. 2. Clean lube oil filter.	Q-1	MM3 FN	2.0 2.0	None
A5 9657 S	1. Test spring loaded exhaust valve by steam.	S-1	MM2 FN	0.2 0.2	W-1
84 5082 A	1. Sound and tighten foundation bolts. 2. Inspect and clean steam strainer.	A-1	MM3	1.0	None
88 Q275 C	1. Inspect internal water lubricated bearing and journal for condition. Measure bearing and propeller clearances.	C-1	MM1 2FN	12.0 24.0	R-1
45 5041 C	1. Inspect condition of bearings and journals. Measure clearances.	C-2	MM1 MM3	17.5 17.5	Q-1
84 5085 C	1. Inspect carbon packing for wear. 2. Inspect turbine exterior.	C-3R	MM2 FN	3.0 3.0	None
55 4087 C	1. Test turbine casing relief valve on main circulator.	C-4	MM3	1.0	None
88 Q274 R	1. Renew packing when gland has been tightened to within 1/4" of pump housing.	R-1	MM3 FN	1.0 1.0	None

MAINTENANCE INDEX PAGE (MIP)
OPNAV 4700-3 (A) (REV. 3/69)

SYSCOM MIP CONTROL NUMBER E-5/78-59

Exhibit 2 - Cycle and Quarterly Schedules

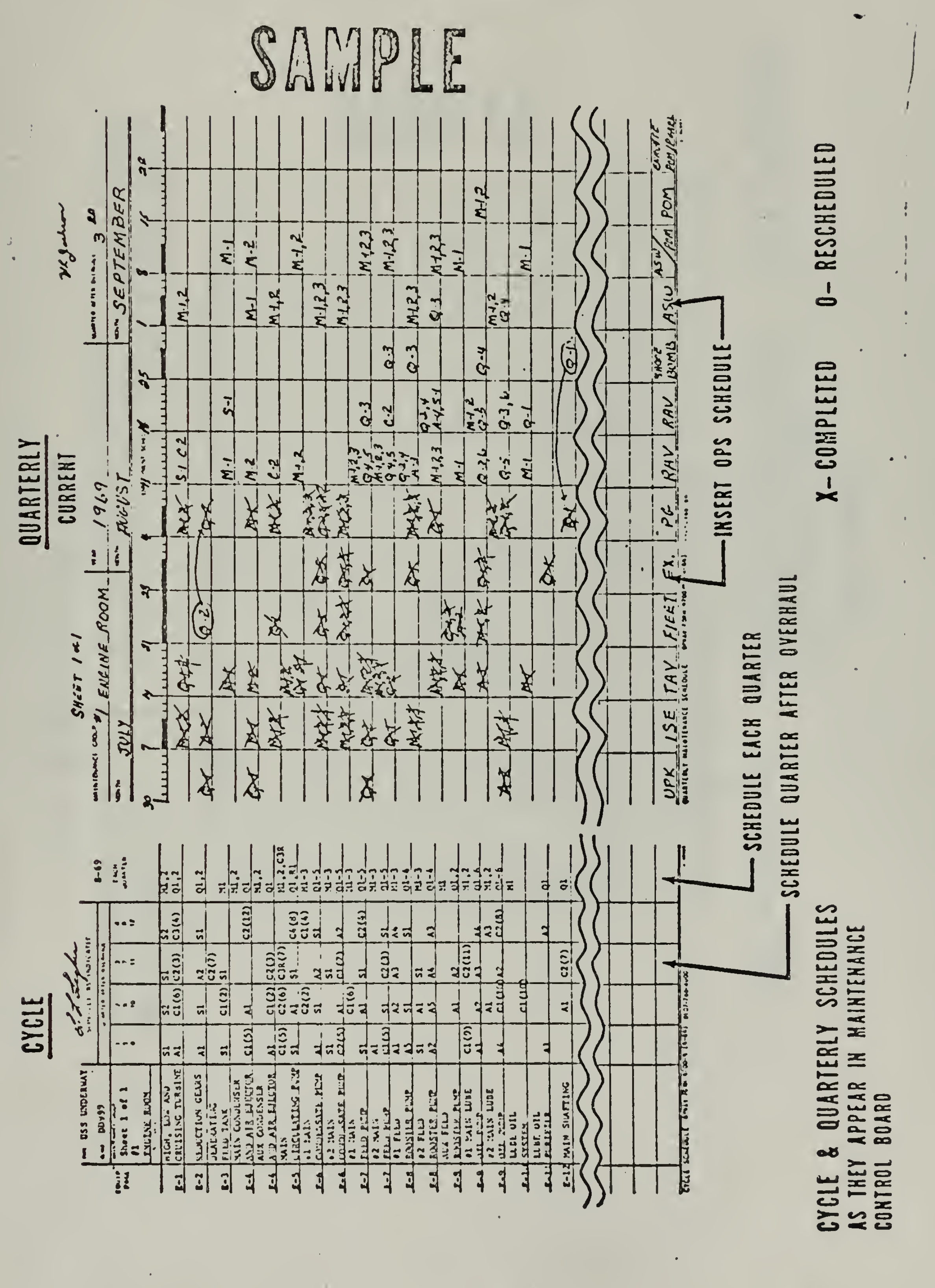


Exhibit 3 - Weekly Schedule

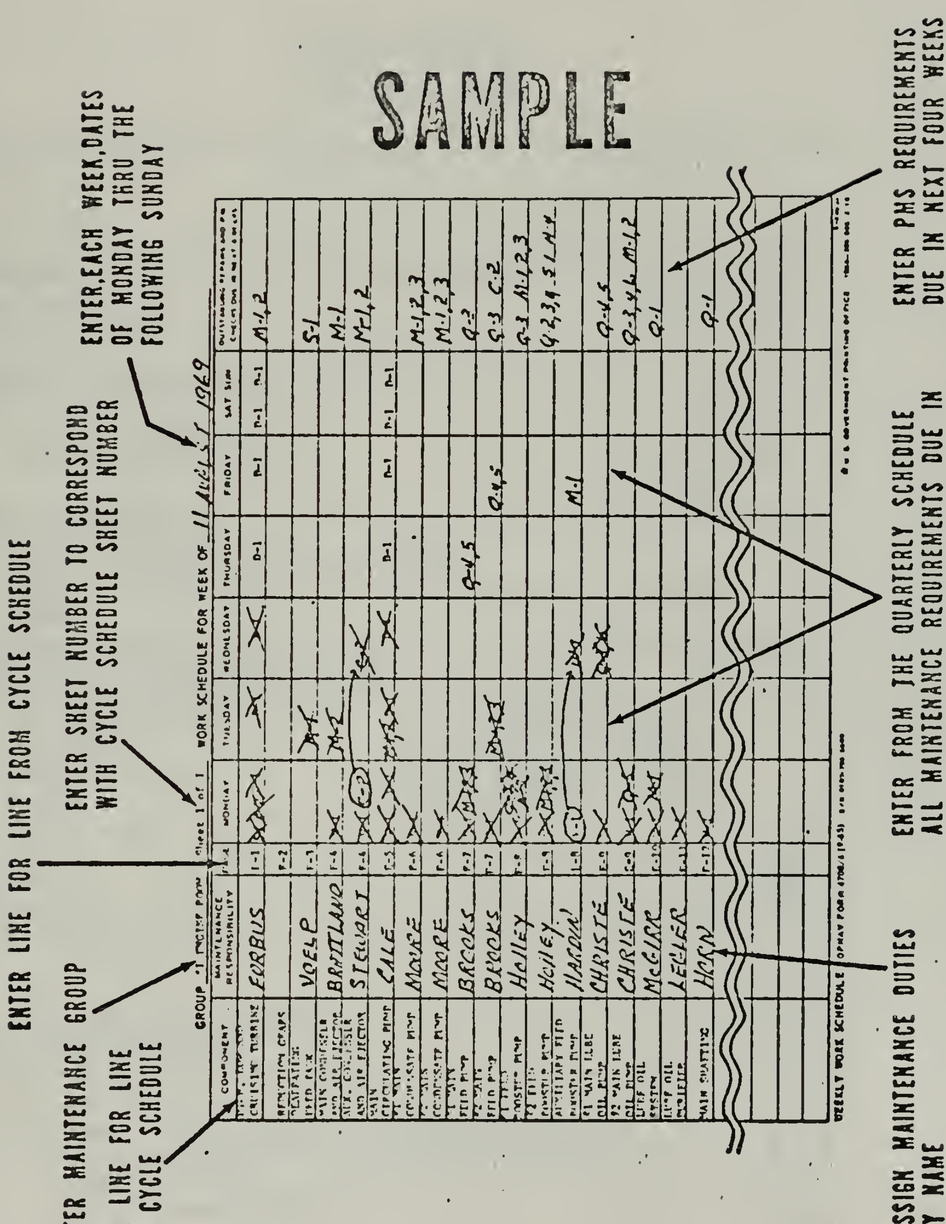


Exhibit 4 - Maintenance Requirement Card

SAMPLE

SYSTEM	COMPONENT	MRC CODE	
Propulsion	Main Circulating Pump	E-5 Q-1	
SUBSYSTEM Circulating and Cooling Water	RELATED MAINTENANCE None	RATES MM3 FN	M/H 2.0 2.0
MAINTENANCE REQUIREMENT DESCRIPTION 1. Clean sump and renew oil. 2. Clean lube oil filter.		TOTAL M/H 4.0 ELAPSED TIME 2.0	

SAFETY PRECAUTIONS
1. Observe standard safety precautions.
2. Wire steam inlet and outlet valves shut and tag "Do Not Open."

TOOLS, PARTS, MATERIALS, TEST EQUIPMENT
1. 13/16" Combination wrench
2. 1/2" Drive socket set
3. Flashlight
4. Lint-free rags
5. Bucket
6. Safety tags
7. Wire, 24 gauge
8. 6" Slip-joint pliers
9. Oil, Symbol 2190 TEP
10. 1/32" Gasket material, Symbol 2290

PROCEDURE

Preliminary
a. Wire steam inlet and outlet valves shut and tag "Do Not Open."

1. Clean Sump and Renew Oil
   a. Drain oil sump.
   b. Remove inspection plate.
   c. Clean out sump.
   d. Ensure sump is clear of foreign material.
   e. Using new gasket on clean surfaces, reinstall inspection plate.
   f. Fill oil sump with oil.

2. Clean Lube Oil Filter
   a. Turn cleaning handle on top of lube oil filter three or four turns.
   b. Remove plug from bottom of filter and drain the sediment.
   c. Reinstall the drain plug.
   d. Remove wire and tags from the steam inlet and outlet valves.

PAGE 1 OF 1

65 8565 Q

LOCATION	DATE
	1 June 1965

MAINTENANCE REQUIREMENT CARD (MRC)
OPNAV 4700-1 (B) (REV. 3/69)

APPENDIX B

OPNAV FORM 4790-2K
(REV. 1/70)

MAINTENANCE DATA FORM

MAINTENANCE ACTION — CHECK ONE: COMPL | DEFER | MORE REQ.

SHIP NAME/HULL NUMBER

SECTION I

JOB CONTROL NUMBER: 1. UNIT I D CODE | 2. WORK CENTER | 3. JOB SEQ NO.

4. EQUIP I D CODE

AS DISCOVERED INFORMATION: 5. FIT | 6. WD | 7. WD DATE YR DAY | 8. STAT

9. IDENTIFICATION NUMBER | 10. AFC/ALL | 11. ALTERATION (SHIP ALT, ORD ALT, FLD CHG, ETC.)

SECTION II — COMPLETED ACTION

12. A/T | 13. MAN HOURS 1/10 | 14. RATING/RATE | 15. COMPLETION DATE YR DAY | 16. STAT | 17. CAUSE | TIME → METER AND COUNTER → EQUIPMENT | 18. ACT. MAINT. TIME 1/10 | 19. TBL ISL | 20. EQUIP METER READING | 21. MTH

SECTION III — DEFERRAL ACTION PLANNING

22. A/T | 23. MAN HOURS 1/10 | 24. RATING/RATE | 25. DEFERRED DATE YR DAY | 26. STAT | 27. AVL | 28. PRL | 29. PR | 30. ACT. MAINT. TIME 1/10 | 31. TBL ISL | 32. EQUIP. METER READING | 33. MTH

34. W/C A/T | 35. REPAIR W.C. | 36. EST. MAN HOURS | 37. ASS'T REPAIR W.C. | 38. ASS'T EST. M/H | 39. AVL | 40. SCHED START DATE YR DAY | 41. SCHED COMPL. DATE YR DAY | 42. REPAIR ACTIVITY U.I.C.

SECTION IV — REMARKS / DESCRIPTION

43. NOUN NAME

INSURV BOARD USE: 44. TIME | 45. CLASSIFICATION NO. | 46. U/S | 47. M

S
T
V
W
X
Y
Z
CONT. SHEET

COMPARTMENT | DECK | FRAME | SIDE | INTEGRATED PRI. | SHEET NO.

1ST CONTACT/MAINT. MAN A. | 2ND CONTACT/SUPERVISOR NAME B. | CO SIGNATURE C.

SECTION V — FAILED PARTS/COMPONENT

48. EIC TO LOA | 49. MFG. PART NO. ☐ FSN ☐ | 50. MFG. CODE | 51. SERIAL NUMBER | 52. F. PT. COND. | 53. REF. SYMBOL | 54. DIS

55. | 56. MFG. PART NO. ☐ FSN ☐ | 57. | 58. | 59. | 60. | 61.

62. | 63. MFG. PART NO. ☐ FSN ☐ | 64. | 65. | 66. | 67. | 68.

SECTION VI — SUPPLEMENTARY INFORMATION

69. BLUEPRINTS, TECH MANUALS, PLANS, ETC. | AVAILABLE ON BOARD YES | NO

70. PREARRIVAL AND/OR ARRIVAL CONFERENCE ACTION- REMARKS

71. SCREENING ACTION: SHIP | SOO | TYCOM

SHOP

EST. M/H

DOC. M/H

LEAD P&E CODE | PLANNER I.D. | DATE OF ESTIMATE — ARRIVAL 2 DAYS

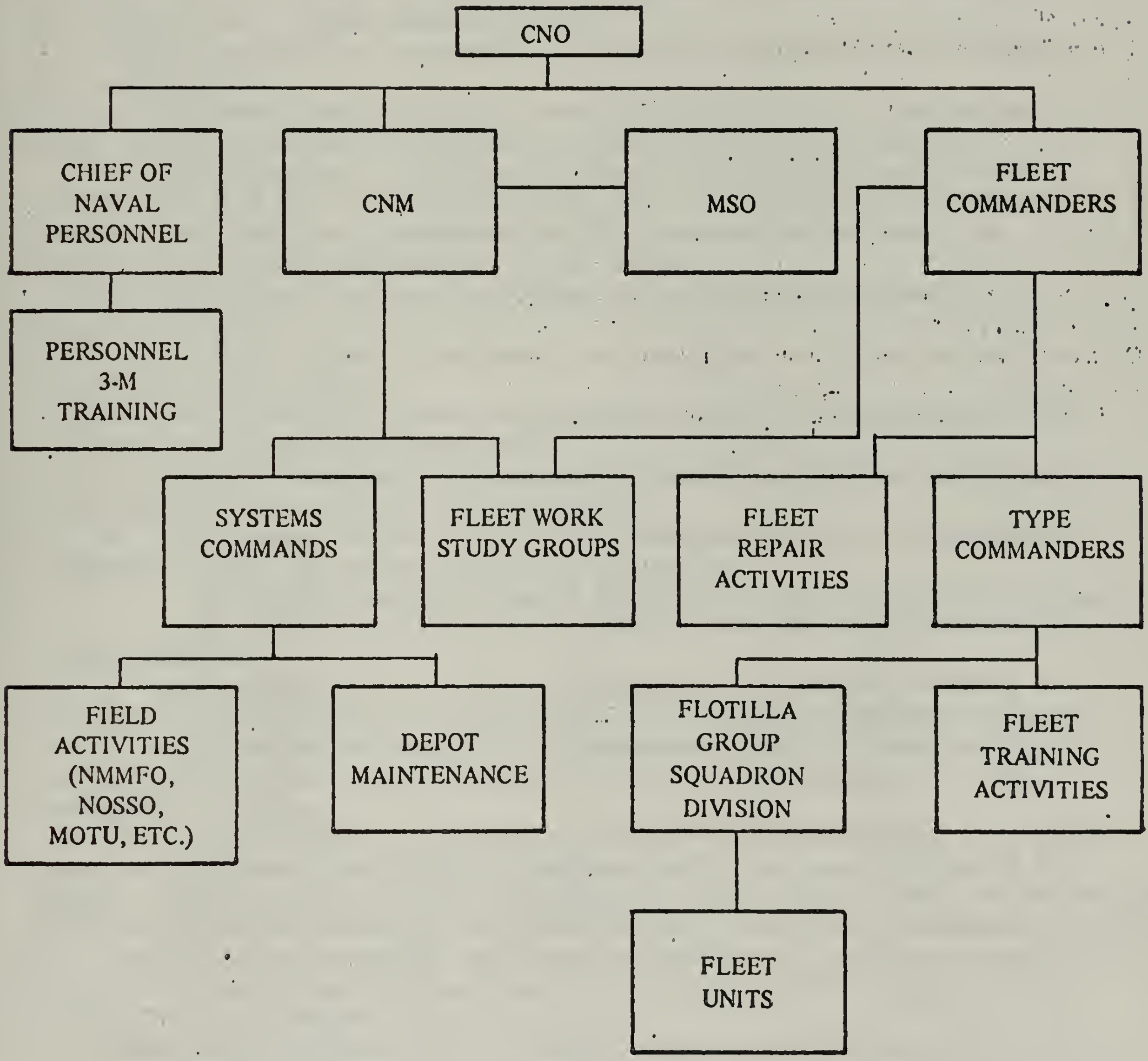
TOTAL MANDAYS | M/D DOLLARS $ | MATERIAL $ | TOTAL COST $

JOB ORDER NUMBER

SOO SIG. D. | TYCOM SIG./REPAIR OFFICER E. | COMPLETED BY F. | ACCEPTED BY G.

APPENDIX C

DEPARTMENT OF THE NAVY
ORGANIZATION FOR 3-M



APPENDIX D

Z-GRAM 46 - REFINEMENT OF SHIPS 3-M MDCS SUB-SYSTEM

1. As part of the continuing effort to reduce the administrative workload on naval personnel in ships, this NAVOP implements the recommendations of the ships 3-M system review group which was appointed by the CNO to further refine the management information system and enhance its overall effectiveness.
2. Within the MDCS sub-system, the following refinements are effective immediately:

A. Equipment identification code reporting will be limited to those codes listed in the EIC master index manual of 1 Jun 70.

B. Submarines will continue to report maintenance actions in accordance with the 3-M manual (OPNAV 43P2) as supplemented by fleet CINCs. The remaining provisions of this program do not apply to these ships unless specified by fleet CINCs.

C. Maintenance actions performed by ships force will not be reported except:

(1) On selected equipment as specified for ships in subparagraph two delta below.

(2) Essential items for material history in accordance with uniform instructions of fleet CINC.

(3) As necessary to maintain a simplifed CSMP in accordance with uniform instructions of fleet CINC.

D. Maintenance actions on selected equipment listed in appendix eighteen of the 3-M manual will be reported by:

(1) Ships less than twenty years since initial commissioning.

(2) All CLG, CG and other special case ships designated by fleet CINCs.

E. Maintenance deferred for performance by agencies external to the ship will continue to be reported by all ships regardless of age.

F. Maintenance deferred for performance by ship's force will be reported at tycom option and in accordance with guidance to be published by tycom.

3. A simplified format using the existing OPNAV 4790/2K and a purified selected equipment list will be implemented in the near future by the Chief of Naval Material, after coordination with fleet CINCs, to reduce the MDCS reporting requirements for deferred and completed maintenance actions.
4. Chief of Naval Material and fleet commanders in chief are requested to provide amplifying instructions to the modified MDCS reporting procedures outlined above.
5. Commanding officers are requested to give wide dissemination within their respective commands to the policies contained herein streamlining MDCS and reducing the administrative workload by approximately forty percent on ships personnel. A 3-M policy committee has been established by OPNAVINST 5200.16 (OP-433 Ser 1270P43 of 23 Sep 70 (NOTAL)) to further review the ship's 3-M system for additional refinements of MDCS and PMS sub-systems.
6. This NAVOP is cancelled when its provisions have been incorporated in a forthcoming change to the 3-M manual and for record purposes not later than 1 February 1971.

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